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Measurement of the Branching Fraction $\mathcal{B}$ ($B_u^+ \rightarrow J/\psi\pi^+$) and Search for $B_c^+ \rightarrow J/\psi\pi^+$

F. Abe et al.
The CDF Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510-0500

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F. Abe,[15] H. Akimoto,[34] A. Akopian,[29] M. G. Albrow,[7] S. R. Amendolia,[25] D. Amidei,[18] J. Antos,[31] C. Anway-Wiese,[4] S. Aota,[34] G. Apollinari,[29] T. Asakawa,[34] W. Ashmanskas,[16] M. Atac,[7] F. Azfar,[24] P. Azzi-Bacchetta,[23] N. Bacchetta,[23] W. Badgett,[18] S. Bagdasarov,[29] M. W. Bailey,[20] J. Bao,[37] P. de Barbaro,[28] A. Barbaro-Galtieri,[16] V. E. Barnes,[27] B. A. Barnett,[14] E. Barzi,[8] G. Bauer,[17] T. Baumann,[10] F. Bedeschi,[25] S. Behrends,[3] S. Belforte,[25] G. Bellettini,[25] J. Bellinger,[36] D. Benjamin,[33] J. Benlloch,[17] J. Bensinger,[3] D. Benton,[24] A. Beretvas,[7] J. P. Berge,[7] J. Berryhill,[5] S. Bertolucci,[8] B. Bevensee,[24] A. Bhatti,[29] K. Biery,[13] M. Binkley,[7] D. Bisello,[23] R. E. Blair,[1] C. Blocker,[3] A. Bodek,[28] W. Bokhari,[17] V. Bolognesi,[2] G. Bolla,[23] D. Bortoletto,[27] J. Boudreau,[26] L. Breccia,[2] C. Bromberg,[19] N. Bruner,[20] E. Buckley-Geer,[7] H. S. Budd,[28] K. Burkett,[18] G. Busetto,[23] A. Byon-Wagner,[7] K. L. Byrum,[1] J. Cammerata,[14] C. Campagnari,[7] M. Campbell,[18] A. Caner,[25] W. Carithers,[16] D. Carlsmith,[36] A. Castro,[23] D. Cauz,[25] Y. Cen,[28] F. Cervelli,[25] P. S. Chang,[31] P. T. Chang,[31] H. Y. Chao,[31] J. Chapman,[18] M. -T. Cheng,[31] G. Chiarelli,[25] T. Chikamatsu,[34] C. N. Chiou,[31] L. Christofek,[12] S. Cihangir,[7] A. G. Clark,[9] M. Cobal,[25] E. Cocca,[25] M. Contreras,[5] J. Conway,[30] J. Cooper,[7] M. Cordelli,[8] C. Couyoumtzelis,[9] D. Crane,[1] D. Cronin-Hennessy,[6] R. Culbertson,[5] T. Daniels,[17] F. DeJongh,[7] S. Delchamps,[7] S. Dell'Agnello,[25] M. Dell'Orso,[25] R. Demina,[7] L. Demortier,[29] B. Denby,[25] M. Deninno,[2] P. F. Derwent,[7] T. Devlin,[30] J. R. Dittmann,[6] S. Donati,[25] J. Done,[32] T. Dorigo,[23] A. Dunn,[18] N. Eddy,[18] K. Einsweiler,[16] J. E. Elias,[7] R. Ely,[16] E. Engels, Jr.,[26] D. Errede,[12] S. Errede,[12] Q. Fan,[27] C. Ferretti,[25] I. Fiori,[2] B. Flaugher,[7] G. W. Foster,[7] M. Franklin,[10]

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M. Frautschi,[33] J. Freeman,[7] J. Friedman,[17] T. A. Fuess,[1] Y. Fukui,[15] S. Funaki,[34] G. Gagliardi,[25] S. Galeotti,[25] M. Gallinaro,[23] M. Garcia-Sciveres,[16] A. F. Garfinkel,[27] C. Gay,[10] S. Geer,[7] D. W. Gerdes,[14] P. Giannetti,[25] N. Giokaris,[29] P. Giromini,[8] G. Giusti,[25] L. Gladney,[24] D. Glenzinski,[14] M. Gold,[20] J. Gonzalez,[24] A. Gordon,[10] A. T. Goshaw,[6] K. Goulianos,[29] H. Grassmann,[25] L. Groer,[30] C. Grosso-Pilcher,[5] G. Guillian,[18] R. S. Guo,[31] C. Haber,[16] E. Hafen,[17] S. R. Hahn,[7] R. Hamilton,[10] R. Handler,[36] R. M. Hans,[37] K. Hara,[34] A. D. Hardman,[27] B. Harral,[24] R. M. Harris,[7] S. A. Hauger,[6] J. Hauser,[4] C. Hawk,[30] E. Hayashi,[34] J. Heinrich,[24] K. D. Hoffman,[27] M. Hohlmann,[5] C. Holck,[24] R. Hollebeek,[24] L. Holloway,[12] A. Hölscher,[13] S. Hong,[18] G. Houk,[24] P. Hu,[26] B. T. Huffman,[26] R. Hughes,[21] J. Huston,[19] J. Huth,[10] J. Hylen,[7] H. Ikeda,[34] M. Incagli,[25] J. Incandela,[7] G. Introzzi,[25] J. Iwai,[34] Y. Iwata,[11] H. Jensen,[7] U. Joshi,[7] R. W. Kadel,[16] E. Kajfasz,[23] H. Kambara,[9] T. Kamon,[32] T. Kaneko,[34] K. Karr,[35] H. Kasha,[37] Y. Kato,[22] T. A. Keaffaber,[27] L. Keeble,[8] K. Kelley,[17] R. D. Kennedy,[30] R. Kephart,[7] P. Kesten,[16] D. Kestenbaum,[10] R. M. Keup,[12] H. Keutelian,[7] F. Keyvan,[4] B. Kharadia,[12] B. J. Kim,[28] D. H. Kim,[7a] H. S. Kim,[13] S. B. Kim,[18] S. H. Kim,[34] Y. K. Kim,[16] L. Kirsch,[3] P. Koehn,[28] K. Kondo,[34] J. Konigsberg,[10] S. Kopp,[5] K. Kordas,[13] A. Korytov,[17] W. Koska,[7] E. Kovacs,[7a] W. Kowald,[6] M. Krasberg,[18] J. Kroll,[7] M. Kruse,[28] T. Kuwabara,[34] S. E. Kuhlmann,[1] E. Kuns,[30] A. T. Laasanen,[27] N. Labanca,[25] S. Lammel,[7] J. I. Lamoureux,[3] T. LeCompte,[1] S. Leone,[25] J. D. Lewis,[7] P. Limon,[7] M. Lindgren,[4] T. M. Liss,[12] N. Lockyer,[24] O. Long,[24] C. Loomis,[30] M. Loreti,[23] J. Lu,[32] D. Lucchesi,[25] P. Lukens,[7] S. Lusin,[36] J. Lys,[16] K. Maeshima,[7] A. Maghakian,[29] P. Maksimovic,[17] M. Mangano,[25] J. Mansour,[19] M. Mariotti,[23] J. P. Marriner,[7] A. Martin,[12] J. A. J. Matthews,[20] R. Mattingly,[17] P. McIntyre,[32] P. Melese,[29] A. Menzione,[25] E. Meschi,[25] S. Metzler,[24] C. Miao,[18] T. Miao,[7] G. Michail,[10] R. Miller,[19] H. Minato,[34] S. Miscetti,[8] M. Mishina,[15] H. Mitsushio,[34] T. Miyamoto,[34] S. Miyashita,[34] N. Moggi,[25] Y. Morita,[15] J. Mueller,[26] A. Mukherjee,[7] T. Muller,[4] P. Murat,[25] H. Nakada,[34] I. Nakano,[34] C. Nelson,[7] D. Neuberger,[4] C. Newman-Holmes,[7] M. Ninomiya,[34] L. Nodulman,[1] S. H. Oh,[6] K. E. Ohl,[37] T. Ohmoto,[11] T. Ohsugi,[11] R. Oishi,[34] M. Okabe,[34] T. Okusawa,[22] R. Oliveira,[24] J. Olsen,[36] C. Pagliarone,[2] R. Paoletti,[25] V. Papadimitriou,[33] S. P. Pappas,[37] N. Parashar,[25] S. Park,[7]

A. Parri,[8] J. Patrick,[7] G. Pauletta,[25] M. Paulini,[16] A. Perazzo,[25] L. Pescara,[23] M. D. Peters,[16] T. J. Phillips,[6] G. Piacentino,[2] M. Pillai,[28] K. T. Pitts,[7] R. Plunkett,[7] L. Pondrom,[36] J. Proudfoot,[1] F. Ptohos,[10] G. Punzi,[25] K. Ragan,[13] D. Reher,[16] A. Ribon,[23] F. Rimondi,[2] L. Ristori,[25] W. J. Robertson,[6] T. Rodrigo,[25] S. Rolli,[25] J. Romano,[5] L. Rosenson,[17] R. Roser,[12] W. K. Sakumoto,[28] D. Saltzberg,[5] A. Sansoni,[8] L. Santi,[25] H. Sato,[34] P. Schlabach,[7] E. E. Schmidt,[7] M. P. Schmidt,[37] A. Scribano,[25] S. Segler,[7] S. Seidel,[20] Y. Seiya,[34] G. Sganos,[13] M. D. Shapiro,[16] N. M. Shaw,[27] Q. Shen,[27] P. F. Shepard,[26] M. Shimojima,[34] M. Shochet,[5] J. Siegrist,[16] A. Sill,[33] P. Sinervo,[13] P. Singh,[26] J. Skarha,[14] K. Sliwa,[35] F. D. Snider,[14] T. Song,[18] J. Spalding,[7] T. Speer,[9] P. Sphicas,[17] F. Spinella,[25] M. Spiropulu,[10] L. Spiegel,[7] L. Stanco,[23] J. Steele,[36] A. Stefanini,[25] K. Strahl,[13] J. Strait,[7] R. Ströhmer,[7a] D. Stuart,[7] G. Sullivan,[5] A. Soumarokov,[31] K. Sumorok,[17] J. Suzuki,[34] T. Takada,[34] T. Takahashi,[22] T. Takano,[34] K. Takikawa,[34] N. Tamura,[11] F. Tartarelli,[25] W. Taylor,[13] P. K. Teng,[31] Y. Teramoto,[22] S. Tether,[17] D. Theriot,[7] T. L. Thomas,[20] R. Thun,[18] M. Timko,[35] P. Tipton,[28] A. Titov,[29] S. Tkaczyk,[7] D. Toback,[5] K. Tollefson,[28] A. Tollestrup,[7] J. F. de Troconiz,[10] S. Truitt,[18] J. Tseng,[14] N. Turini,[25] T. Uchida,[34] N. Uemura,[34] F. Ukegawa,[24] G. Unal,[24] J. Valls,[7a] S. C. van den Brink,[26] S. Vejcik, III,[18] G. Velev,[25] R. Vidal,[7] M. Vondracek,[12] D. Vucinic,[17] R. G. Wagner,[1] R. L. Wagner,[7] J. Wahl,[5] N. Wallace,[25] C. Wang,[6] C. H. Wang,[31] J. Wang,[5] M. J. Wang,[31] Q. F. Wang,[29] A. Warburton,[13] T. Watts,[30] R. Webb,[32] C. Wei,[6] C. Wendt,[36] H. Wenzel,[16] W. C. Wester, III,[7] A. B. Wicklund,[1] E. Wicklund,[7] R. Wilkinson,[24] H. H. Williams,[24] P. Wilson,[5] B. L. Winer,[21] D. Winn,[18] D. Wolinski,[18] J. Wolinski,[19] S. Worm,[20] X. Wu,[9] J. Wyss,[23] A. Yagil,[7] W. Yao,[16] K. Yasuoka,[34] Y. Ye,[13] G. P. Yeh,[7] P. Yeh,[31] M. Yin,[6] J. Yoh,[7] C. Yosef,[19] T. Yoshida,[22] D. Yovanovitch,[7] I. Yu,[7] L. Yu,[20] J. C. Yun,[7] A. Zanetti,[25] F. Zetti,[25] L. Zhang,[36] W. Zhang,[24] and S. Zucchelli[2]

(CDF Collaboration)

[1] *Argonne National Laboratory, Argonne, Illinois 60439*

[2] *Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40126 Bologna, Italy*

[3] *Brandeis University, Waltham, Massachusetts 02254*

[4] *University of California at Los Angeles, Los Angeles, California 90024*

[5] *University of Chicago, Chicago, Illinois 60637*

[6] *Duke University, Durham, North Carolina 27708*

[7] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

[8] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*

[9] *University of Geneva, CH-1211 Geneva 4, Switzerland*

[10] *Harvard University, Cambridge, Massachusetts 02138*

[11] *Hiroshima University, Higashi-Hiroshima 724, Japan*

[12] *University of Illinois, Urbana, Illinois 61801*

[13] *Institute of Particle Physics, McGill University, Montreal H3A 2T8, and University of Toronto, Toronto M5S 1A7, Canada*

[14] *The Johns Hopkins University, Baltimore, Maryland 21218*

[15] *National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan*

[16] *Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*

[17] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

[18] *University of Michigan, Ann Arbor, Michigan 48109*

[19] *Michigan State University, East Lansing, Michigan 48824*

[20] *University of New Mexico, Albuquerque, New Mexico 87131*

[21] *The Ohio State University, Columbus, OH 43210*

[22] *Osaka City University, Osaka 588, Japan*

[23] *Universita di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*

[24] *University of Pennsylvania, Philadelphia, Pennsylvania 19104*

[25] *Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*

[26] *University of Pittsburgh, Pittsburgh, Pennsylvania 15260*

[27] *Purdue University, West Lafayette, Indiana 47907*

[28] *University of Rochester, Rochester, New York 14627*

[29] *Rockefeller University, New York, New York 10021*

[30] *Rutgers University, Piscataway, New Jersey 08854*

[31] *Academia Sinica, Taipei, Taiwan 11529, Republic of China*

[32] *Texas A&M University, College Station, Texas 77843*

[33] *Texas Tech University, Lubbock, Texas 79409*

[34] *University of Tsukuba, Tsukuba, Ibaraki 305, Japan*

[35] *Tufts University, Medford, Massachusetts 02155*

[36] *University of Wisconsin, Madison, Wisconsin 53706*

[37] *Yale University, New Haven, Connecticut 06511*

We report on a measurement of the branching fraction of the Cabibbo-suppressed decay $B_u^+ \to J/\psi\pi^+$, where $J/\psi \to \mu^-\mu^-$. The data were collected by the Collider Detector at Fermilab during 1992–1995 and correspond to an integrated luminosity of 110 pb^{-1} in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. A signal of 28^{+10}_{-9} events is observed and we determine the ratio of branching fractions $\mathcal{B}(B_u^+ \to J/\psi\pi^+)/\mathcal{B}(B_u^+ \to J/\psi K^+)$ to be $(5.0^{+1.9}_{-1.7} \pm 0.1)\%$, where the first uncertainty is statistical and the second is systematic. Using the world average value for $\mathcal{B}(B_u^+ \to J/\psi K^+)$, we calculate the branching fraction $\mathcal{B}(B_u^+ \to J/\psi\pi^+)$ to be $(5.0^{+2.1}_{-1.9}) \times 10^{-5}$. We also search for the decay $B_c^+ \to J/\psi\pi^+$ and report a 95% confidence level limit on $\sigma(B_c^+) \cdot \mathcal{B}(B_c^+ \to J/\psi\pi^+)/\sigma(B_u^+) \cdot \mathcal{B}(B_u^+ \to J/\psi K^+)$ as a function of the B_c^+ lifetime.

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This Letter reports on the reconstruction of the Cabibbo-suppressed decay $B_u^+ \to J/\psi\pi^+$ [1] and the measurement of the ratio of branching fractions, $\mathcal{B}(B_u^+ \to J/\psi\pi^+)/\mathcal{B}(B_u^+ \to J/\psi K^+)$. The Cabibbo-suppressed mode, which has been previously reported by the CLEO Collaboration [2], provides a valuable test of the factorization hypothesis [3], which is widely used in theoretical considerations of B meson decays. According to this hypothesis, we expect $\mathcal{B}(B_u^+ \rightarrow J/\psi\pi^+)/\mathcal{B}(B_u^+ \rightarrow J/\psi K^+)$ to be about 5%. This decay mode may show CP violating effects at the few percent level because the suppression of the dominant spectator amplitude enhances interference with nonleptonic penguin amplitudes [4]. We also search for the unobserved charmed bottom meson, B_c^-, decaying to the same final state. A 95% confidence level limit for the ratio of cross sections times branching fractions $\sigma(B_c^+)\cdot\mathcal{B}(B_c^- \rightarrow J/\psi\pi^+)/\sigma(B_u^+)\cdot\mathcal{B}(B_u^+ \rightarrow J/\psi K^+)$ is reported as a function of the assumed B_c^+ lifetime. By forming these ratios, we minimize several systematic uncertainties, the largest of which are associated with the b-quark production cross section and transverse momentum spectrum.

The B_c^+ is the bound state of the bottom and charm ($\bar{b}$ and c) quarks and is predicted to exist by the Standard Model. The mass of the B_c^- is predicted to be 6.258 ± 0.020 GeV/c^2 [5] with a lifetime of 0.4–1.4 ps [6,7]. The B_c^- mass measurement will test our understanding of the potential model used to calculate quark bound state masses and the lifetime measurement will give information on the effect of binding on lifetime and test the accuracy of the spectator model assumption.

Perturbative QCD calculations indicate that spectator $\bar{c}c$ production is highly suppressed in b-quark hadronization due to the heavy charm quark mass. The fraction of b-quarks that hadronize to produce B_c^+ mesons is estimated to be $\sim 1.5\times10^{-3}$ [8] from cross section calculations. However, the large branching fraction of B_c^+ to inclusive J/ψ final states compared with that for lighter B mesons enhances our ability to detect this mode. The branching fraction of $B_c^+ \rightarrow J/\psi\pi^+$ is estimated to be 0.2% [9]. Based on these calculations, the Cabibbo-suppressed $B_u^+ \rightarrow J/\psi\pi^+$ yield is estimated to be greater than the $B_c^+ \rightarrow J/\psi\pi^+$ yield by a factor of $\sim$7 [10].

The data used in this analysis were collected with the Collider Detector at Fermilab (CDF) during the 1992–1995 run, and correspond to an integrated luminosity of 110 pb^{-1} of $\bar{p}p$ collisions at $\sqrt{s}=1.8$ TeV. The CDF detector is described in detail elsewhere [11]. We describe the components of the detector that are important for this analysis. The silicon vertex detector (SVX) and the central tracking chamber (CTC) provide spatial measurements in the r-φ plane [12], giving an average track impact parameter resolution of $\sim (16^2 + (28/P_T)^2)^{1/2}$ μm for tracks transverse to the beam axis, where P_T is the track transverse momentum in units of GeV/c. The P_T resolution of the CTC combined with the SVX is $\delta(P_T)/P_T = ((0.0009P_T)^2 + 0.0066^2)^{1/2}$ [13]. To identify muon candidates, two muon subsystems are used, which together provide coverage in the pseudorapidity interval $|\eta| < 1.0$, where pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$. The dimuon trigger requires that two oppositely charged CTC tracks each match muon track segments and that the $\mu^+\mu^-$ invariant mass is between 2.8 and 3.4 GeV/c^2 to select J/ψ candidates [13].

We first describe the $B_u^+ \to J/\psi\pi^+$ analysis. Reconstruction of the B_u^+ starts with the isolation of the J/ψ signal. First, muon candidates are identified by matching hits in the muon chamber to extrapolated CTC tracks. Only well measured tracks in the CTC are used and good quality SVX information is added when available, which is the case for approximately 60% of the candidates. Two oppositely charged muon candidates are constrained to originate from a common point in space ("vertex constraint"). The confidence level (CL) of the fit is required to be greater than 1% and the calculated invariant mass of the dimuon pair is required to be within 3 standard deviations (3σ) of the J/ψ world average mass 3.09688 GeV/c^2 [14]. We find $402\,500 \pm 700$ J/ψ candidates with a mass measurement resolution, σ, of ~ 19 MeV/c^2.

We then constrain the dimuons to the J/ψ world average mass, retaining the vertex constraint ("mass and vertex constraint"). A CL $> 1\%$ is required on the mass and vertex constrained fit. All other charged tracks within the CTC fiducial volume are considered as pion and kaon candidates in the reconstruction of the $J/\psi\pi^+$ and $J/\psi K^+$ decay modes, respectively. To reduce combinatoric background and optimize the Cabibbo-suppressed signal's expected statistical significance, we require all pion and kaon candidate tracks to have $P_T(K^+, \pi^+) > 1.25$ GeV/c and we require $P_T(B_u^+) > 5$ GeV/c. Since CDF does not have particle identification to adequately discriminate pions and kaons in this momentum range, each three-track vertex is reconstructed under the $J/\psi\pi^+$ and $J/\psi K^+$ hypothesis, yielding two invariant masses for each three-track combination. To improve our mass measurement resolution, we require that the three tracks form a vertex and constrain their momentum in the r-φ plane to "point" back to the primary vertex, which has been estimated using the average beam position. The "pointing" constraint requires the momentum vector of the three-track combination to have the same direction as the displacement vector from the primary to the secondary vertex. The fit is required to have a CL > 1% and the three-track vertex is subsequently referred to as the secondary vertex. We define the transverse decay length $L_T = \vec{x} \cdot \frac{\vec{P}_T}{|\vec{P}_T|}$ where $\vec{x}$ is the displacement vector from the primary to the secondary vertex and $\vec{P}_T$ is the reconstructed transverse momentum of the B_u^+. To separate the long-lived B_u^+ mesons from the prompt background, we require $L_T(B_u^+) > 150\ \mu$m and the impact parameter significance $d/\sigma_d > 1.0$ for the pion or kaon candidate, where d is the distance of closest approach in two dimensions to the primary vertex and σ_d is the uncertainty, which combines measurement uncertainties on the track and vertex ($\sim 35\ \mu$m). We use L_T rather than the proper flight distance $c\tau$ because no knowledge of the particle mass is needed.

The measurement of the ratio of branching fractions $r_{\rm obs} = \mathcal{B}(B_u^+ \to J/\psi\pi^+)/\mathcal{B}(B_u^+ \to J/\psi K^+)$ involves fitting two mass distributions that differ only in the assignment of the "third track" as a pion or kaon. A maximum likelihood fitting procedure is used to extract the ratio of branching fractions [15]. The likelihood function for event i is

$$\mathcal{L}_i = f_s \left[\frac{1}{1+r_{\rm obs}} G(M_{J/\psi K}, M_B) + \frac{r_{\rm obs}}{1+r_{\rm obs}} G(M_{J/\psi\pi}, M_B) \frac{dM_{J/\psi\pi}}{dM_{J/\psi K}}\right] + (1-f_s) Y_{\rm bkg}, \qquad (1)$$

where f_s is the fraction of signal events in the sample and M_B is the measured B_u^+ mass. $G(M_{J/\psi K}, M_B)$ and $G(M_{J/\psi\pi}, M_B)$ are Gaussian distributions centered on M_B. The quantities $M_{J/\psi\pi^+}$ and $M_{J/\psi K^+}$ are the calculated masses of the J/ψ combined with a charged track considered as a pion and kaon, respectively. $Y_{\rm bkg}$ is a normalized linear term that represents the background distribution and is determined from the $J/\psi K^+$ mass distribution, which is well fit by a Gaussian distribution and a simple linear term. The term $\frac{dM_{J/\psi\pi}}{dM_{J/\psi K}}$, necessary to normalize the likelihood function, is the Jacobian of the transformation between $M_{J/\psi\pi^+}$ and $M_{J/\psi K^+}$ and is equivalent to the ratio of mass uncertainties, $\sigma(M_{J/\psi\pi^+})/\sigma(M_{J/\psi K^+})$.

The fit to 925 events in the $J/\psi K^+$ and $J/\psi\pi^+$ mass distributions with 5.2 GeV/c^2 <

$M_{J/\psi K^+} < 5.6$ GeV/c^2 returns the signal fraction, $f_s = 0.62 \pm 0.02$, and the ratio of branching fractions, $r_{obs} = 5.1^{+1.9}_{-1.7}\%$. This gives us 546 ± 24 signal events in the $B_u^+ \rightarrow J/\psi K^+$ decay mode and 28^{+10}_{-9} in the $B_u^+ \rightarrow J/\psi\pi^-$ decay mode. The $J/\psi K^+$ mass distribution is shown in Fig. 1 and the $J/\psi\pi^+$ mass distribution with superimposed curves generated from a Monte Carlo simulation is shown in Fig. 2.

The ratio of branching fractions must be corrected for the relative tracking efficiencies, which depend on the different decay-in-flight properties of the two decay modes and the slightly different track momentum spectra. A Monte Carlo model with a b-quark P_T-spectrum generated from a next-to-leading order QCD calculation [16] is used to generate events to determine the magnitude of these effects. Simulated charged tracks are imbedded into data events containing a J/ψ with its vertex displaced from the primary vertex in order to approximate the tracking environment of B meson events. Applying the full pattern recognition and track fitting algorithm to the event, the track reconstruction efficiency for pions and kaons is determined. The procedure gives a relative tracking efficiency $\epsilon_{rel} = \epsilon_{J/\psi\pi^+}/\epsilon_{J/\psi K^+} = 0.997 \pm 0.002$ for B_u^+ reconstruction in the absence of decay-in-flight and a decay-in-flight correction $D_{rel} = D_\pi/D_K = 1.028 \pm 0.005$, where D_π and D_K are the efficiencies for reconstructing tracks that may decay within the tracking volume.

The principal systematic uncertainties on the ratio of branching fractions are due to three sources. Uncertainties in the shape of the background are estimated to contribute 0.8% uncertainty to the ratio by allowing alternative background shapes in the likelihood fit. Uncertainties in the normalization correction term, $\frac{dM_{J/\psi\pi}}{dM_{J/\psi K}}$, are estimated by comparing the ratio of mass uncertainties to theoretical expectations based on the assumption that the particles originate from a B_u^+ decay. We estimate an uncertainty of 1.6% from this source. The track reconstruction efficiency has been studied as a function of instantaneous luminosity and its systematic effect on the decay-in-flight correction is estimated to be 1.2% by varying the average luminosity within a reasonable range. The total systematic uncertainty, summarized in Table I, is determined by adding the separate uncertainties in quadrature and is 2.2%. The ratio of branching fractions is determined to be

$$\frac{\mathcal{B}(B_u^+ \to J/\psi\pi^+)}{\mathcal{B}(B_u^+ \to J/\psi K^+)} = (5.0^{+1.9}_{-1.7} \pm 0.1)\%. \tag{2}$$

We then use the world average value for $\mathcal{B}(B^+ \to J/\psi K^+) = (1.01 \pm 0.14) \times 10^{-3}$ [14] to obtain the Cabibbo-suppressed branching fraction

$$\mathcal{B}(B_u^+ \to J/\psi\pi^+) = (5.0^{+2.1}_{-1.9}) \times 10^{-5}. \tag{3}$$

The search for the decay mode $B_c^+ \to J/\psi\pi^+$ begins by defining a mass region of ± 150 MeV/c^2 around the predicted mass of 6.258 GeV/c^2 [5]. To take advantage of the heavier B_c^+ mass relative to the B_u^+ mass, the $B_c^+ \to J/\psi\pi$ candidates must have $P_T(\pi^+) > 2.5$ GeV/c and $P_T(B_c^+) > 6$ GeV/c. Due to the unknown B_c^+ lifetime, four different $c\tau$ selections are used for seven different assumed B_c^+ lifetimes. These are summarized in Table II. The mass distribution for $J/\psi\pi^+$ candidates in the range of interest for the B_c^+ is shown inset in Fig. 2.

To determine the expected mass resolution for the B_c^+, a Monte Carlo study of the CDF detector response for B_u^+ and B_c^+ decays was performed. The ratio of the resolutions obtained was used to scale the observed resolution of the B_u^+ mass, obtaining an estimated B_c^+ mass resolution of 20 MeV/c^2.

The four consecutive 20 MeV/c^2-wide bins in the search region containing the largest number of events are used to calculate the limit on B_c^+ production. The number of events in these four bins is N_{tot}. The remaining events are fit to a linear background function in order to estimate the number of background events N_{bkg} contributing to N_{tot}.

The selection criteria for the reference mode $B_u^+ \to J/\psi K^+$ are modified to require $c\tau > 150$ μm and $P_T(K^+) > 1.5$ GeV/c to reduce systematic uncertainties associated with the B meson momentum spectra [17]. The decay-in-flight correction is recomputed to be $D_{\text{rel}} = 1.035 \pm 0.006$ using the procedure described earlier. The relative efficiency for finding the $B_c^+ \to J/\psi\pi^+$ compared to the $B_u^+ \to J/\psi K^+$ decay mode, ϵ_{rel}, is determined as a function of the B_c^+ lifetime. A Monte Carlo event generator [16] and detector simulation package is used for both types of mesons and the results are presented in Table II. The input $\bar{b}$-quark momentum spectrum and fragmentation to the B mesons are varied to determine a systematic uncertainty of 4% on $\epsilon_{\rm rel}$. The fragmentation of $b \to B_c^+$ uses a perturbative QCD calculation [8] and the uncertainty on this calculation is not included in the systematic uncertainties associated with $\epsilon_{\rm rel}$. The trigger simulation is vairied to determine a systematic uncertainty of 4.3% on $\epsilon_{\rm rel}$.

The $\epsilon_{\rm rel}$ must be corrected for the assumed lifetime of the B_c^+. The $c\tau$ distribution of background events with zero lifetime is fit to a Gaussian distribution to determine the measurement uncertainty. This parameterization is used to convolve the exponential $c\tau$ distribution for the B_c^+ and B_u^+. The ratio of the probabilities for the B_c^+ and B_u^+ to meet the $c\tau$ selection criteria is determined from the distributions for a given B_c^+ lifetime. This ratio adjusts $\epsilon_{\rm rel}$ and contributes a 1.3% systematic uncertainty for short-lived B_c^+ mesons and less for longer-lived ones.

Calculation of the 95% confidence level limit employs the method described in reference [18]. This method assumes Poisson distributions for the signal and background and accounts for the uncertainty in $N_{\rm bkg}$, the uncertainties in the estimate of $\epsilon_{\rm rel}$, and the statistical uncertainty in the number of $J/\psi K^+$ obtained. The relative number of $J/\psi K^+$ that are lost due to decays-in-flight is determined as described earlier. The 95% CL limit on the ratio $\sigma(B_c^+) \cdot \mathcal{B}(B_c^+ \to J/\psi\pi^+)/\sigma(B_u^+) \cdot \mathcal{B}(B_u^+ \to J/\psi K^+)$ as a function of the B_c^+ lifetime is shown in Fig. 3 and Table II. Also shown is an estimate of this ratio when it is assumed that B_c^+ mesons are produced 1.5×10^{-3} [8] times as often as all other B mesons and that the partial width $\Gamma(B_c^+ \to J/\psi\pi^+) = 4.2 \times 10^9~{\rm s}^{-1}$ [19].

In summary, we have observed the Cabibbo-suppressed decay $B_u^+ \to J/\psi\pi^+$ and measured the ratio $\mathcal{B}(B_u^+ \to J/\psi\pi^+)/\mathcal{B}(B_u^+ \to J/\psi K^+)$ to be $(5.0^{+1.9}_{-1.7} \pm 0.1)\%$, which is in good agreement with the measurement from CLEO of $(4.3 \pm 2.3)\%$ [2]. This is also consistent with the theoretical estimate based on factorization [3]. We have used the world average value for $\mathcal{B}(B_u^+ \to J/\psi K^+)$ to calculate $\mathcal{B}(B_u^+ \to J/\psi\pi^+) = (5.0^{+2.1}_{-1.9}) \times 10^{-5}$. In addition, we have searched for $B_c^+ \to J/\psi\pi^+$ and have presented a 95% confidence level limit on $\sigma(B_c^+) \cdot \mathcal{B}(B_c^+ \to J/\psi\pi^+)/\sigma(B_u^+) \cdot \mathcal{B}(B_u^+ \to J/\psi K^+)$ as a function of the B_c^+ lifetime. Based on theoretical predictions of the lifetime and cross section and the limit we have established, the B_c^+ should be observed at CDF with the large data set (~ 2 fb^{-1}) expected from the next running period.

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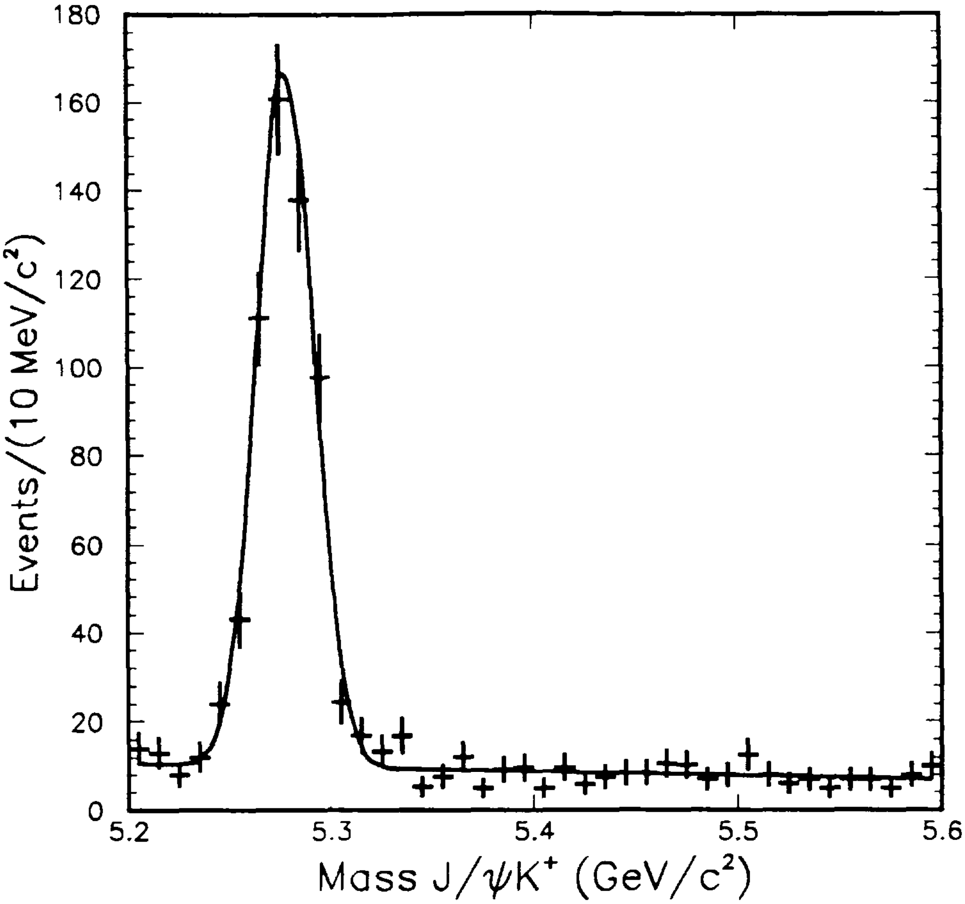

FIG. 1.

The $J/\psi K^+$ mass distribution. There are 546 ± 24 $J/\psi K^+$ signal events. The solid line shows the fit to the data with a Gaussian distribution for the signal and a linear background distribution. The $B_u^+ \to J/\psi\pi^+$ events have been removed.

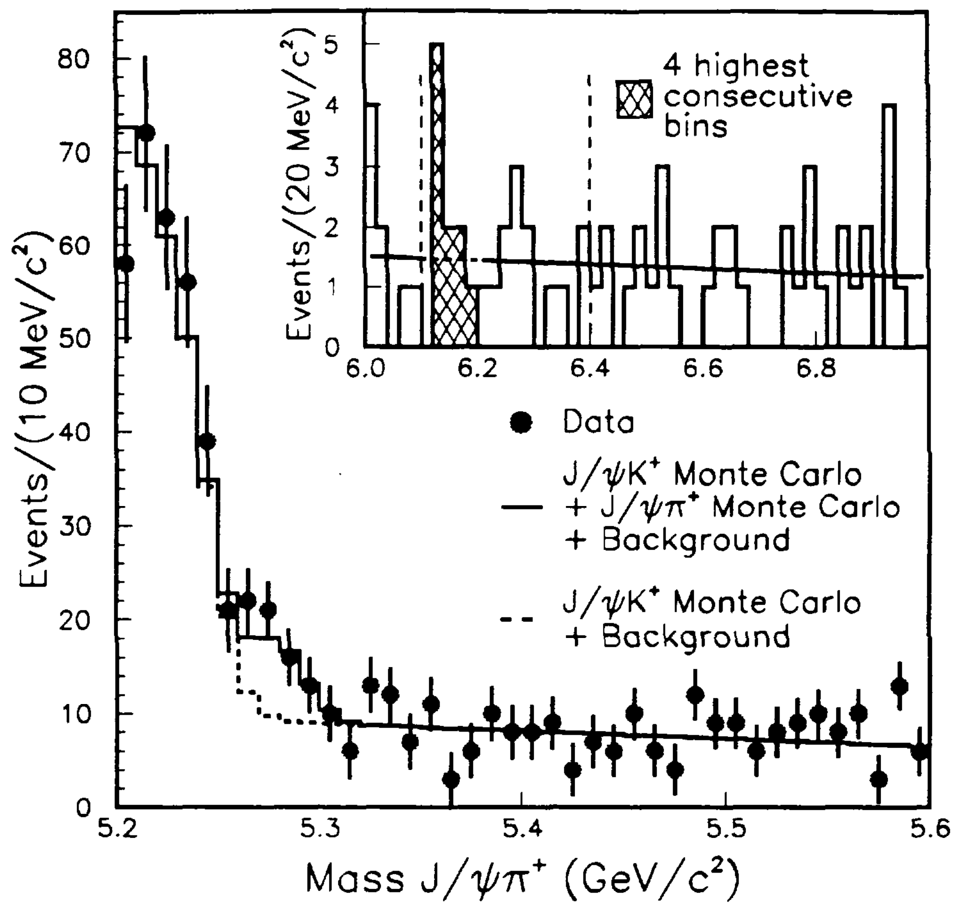

FIG. 2.

The $J/\psi\pi^+$ mass distribution. There are 28^{+10}_{-9} $B_u^- \to J/\psi\pi^+$ signal events. The $B_u^+ \to J/\psi K^+$ signal makes a large contribution to the lower edge of the distribution in the main plot. The superimposed curves show the $J/\psi\pi^+$ mass distribution for Monte Carlo $B_u^+ \to J/\psi K^+$ and background events, with and without Monte Carlo $B_u^+ \to J/\psi\pi^+$ events. Shown inset in the figure is the $J/\psi\pi^+$ mass distribution for the B_c^- search region, with $c\tau > 150$ μm. The search region is delimited by the vertical dashed lines. The solid line parameterizes the background over the domain, excluding the four highest consecutive bins (hatched).

TABLE I. The table summarizes the systematic uncertainties (%) for the ratios of branching fractions, $\mathcal{B}(B_u^+ \to J/\psi\pi^+)/\mathcal{B}(B_u^+ \to J/\psi K^-)$ and $\mathcal{B}(B_c^+ \to J/\psi\pi^+)/\mathcal{B}(B_u^+ \to J/\psi K^+)$.

Quantity	Source	B_u^+ Value (%)	B_c^+ Value (%)
$r_{\rm obs}$	Background Parameterization	0.8	0.8
	Mass Uncertainty Correction	1.6	-
$D_{\rm rel}$	Luminosity Effects	1.2	1.2
	$P_T(B)$ Spectrum	0.5	0.5
$\epsilon_{\rm rel}$	$P_T(B)$ Spectrum	0.3	4.3
	Trigger Simulation	-	4.0
	$c\tau$ Parameterization	-	0.2–1.3
Total		2.2	6.1–6.2

TABLE II. The table shows the chosen B_c^- lifetime, the $c\tau$ selection used, the relative efficiency of the selection criteria ($\epsilon_{\rm rel}$), the total number of data events in the largest 4 consecutive bins from 6.1 to 6.4 GeV/c^2 ($N_{\rm tot}$), the number of background events in those 4 bins ($N_{\rm bkg}$), and the 95% CL limit for the ratio of $\sigma \cdot \mathcal{B}$. The error on $N_{\rm bkg}$ is statistical only.

Lifetime	$c\tau$ cut	$\epsilon_{\rm rel} \equiv \frac{\epsilon(B_u^+)}{\epsilon(B_c^+)}$	$N_{\rm tot}$	$N_{\rm bkg}$	95% CL
0.17 ps	60 μm	2.50 ± 0.15	40	29.2 ± 2.6	0.15
0.33 ps	85 μm	2.10 ± 0.12	25	16.5 ± 2.1	0.10
0.50 ps	100 μm	1.84 ± 0.11	18	12.7 ± 1.7	0.070
0.80 ps	150 μm	1.80 ± 0.10	10	5.9 ± 1.2	0.053
1.0 ps	150 μm	1.61 ± 0.09	10	5.9 ± 1.2	0.046
1.3 ps	150 μm	1.43 ± 0.08	10	5.9 ± 1.2	0.042
1.6 ps	150 μm	1.35 ± 0.07	10	5.9 ± 1.2	0.040

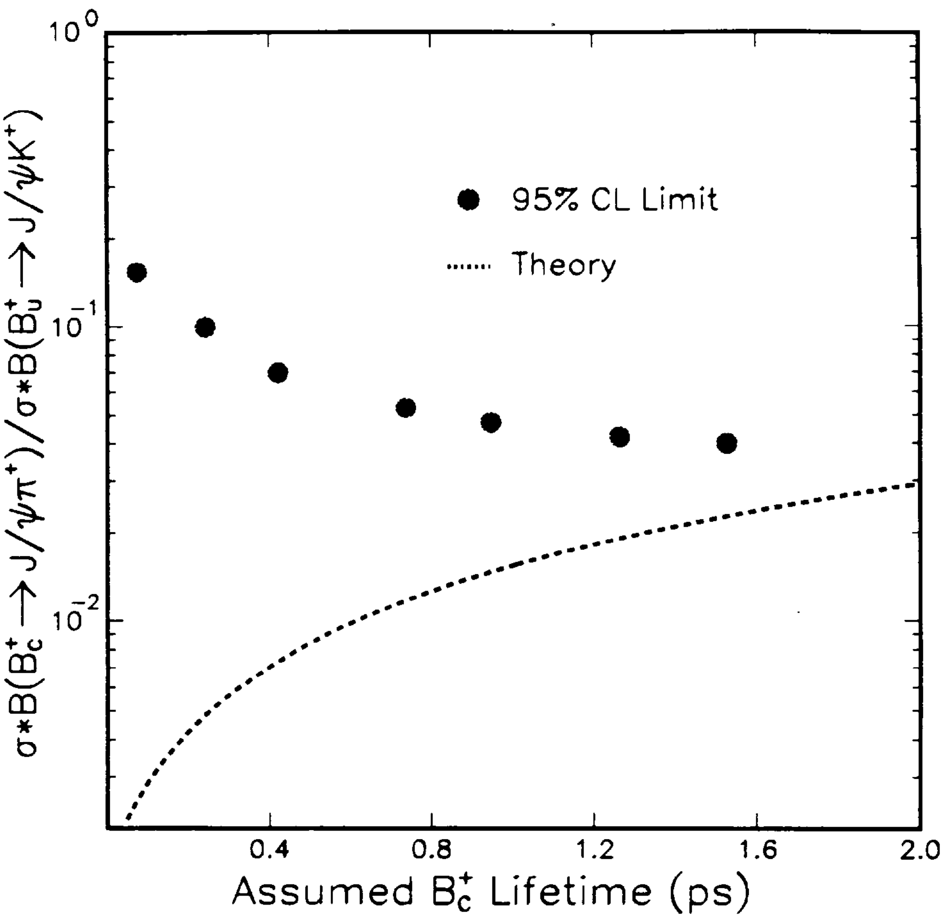

FIG. 3.

The circular points show the different 95% CL limits on the ratio of cross section times branching fraction for $B_c^+ \rightarrow J/\psi\pi^+$ relative to $B_u^+ \rightarrow J/\psi K^+$ as a function of the B_c^+ lifetime. The dotted curve represents a calculation of this ratio based on the assumption that the B_c^+ is produced 1.5×10^{-3} times as often as all other B mesons and that $\Gamma(B_c^+ \rightarrow J/\psi\pi^+) = 4.2 \times 10^9$ s^{-1}.