Bottom Production in π^--Be Collisions at 515 GeV/c

R. Jesik,[3] V. Abramov,[2] Yu. Antipov,[2] B. Baldin,[2] R. Crittenden,[4] L. Dauwe,[6] C. Davis,[5] S. Denisov,[2] A. Dyshkant,[2] A. Dzierba,[4] V. Glebov,[2] H. Goldberg,[3] A. Gribushin,[4] V. Koreshev,[2] J. Krider,[1] A. Krinitsyn,[2] R. Li,[4] S. Margulies,[3] T. Marshall,[4] J. Martin,[4] H. Mendez,[3] A. Petrukhin,[2] V. Sirotenko,[2] P. Smith,[4] J. Solomon,[3] T. Sulanke,[4] R. Sulyaev,[2,*] F. Vaca,[3] and A. Zieminski[4]

(E672 Collaboration)

S. Blusk,[12] C. Bromberg,[9] P. Chang,[10] B.C. Choudhary,[8] W.H. Chung,[12] L. de Barbaro,[13] W. Dlugosz,[10] J. Dunlea,[13] E. Engels, Jr.,[12] G. Fanourakis,[13] G. Ginther,[13] K. Hartman,[11] J. Huston,[9] V. Kapoor,[8] C. Lirakis,[10] F. Lobkowicz,[13] S. Mani,[7] J. Mansour,[13] A. Maul,[9] R. Miller,[9] B. Oh,[11] E. Pothier,[10] R. Roser,[13] P. Shepard,[12] D. Skow,[1] P. Slattery,[13] L. Sorrell,[9] W. Toothacker,[11] N. Varelas,[13] D. Weerasundara,[12] J. Whitmore,[11] C. Yosef,[9] and M. Zielinski[13]

(E706 Collaboration)

[1]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[2]*Institute of High Energy Physics, Serpukhov, Russia*
[3]*University of Illinois at Chicago, Chicago, Illinois 60680*
[4]*Indiana University, Bloomington, Indiana 47405*
[5]*University of Louisville, Louisville, Kentucky 40292*
[6]*University of Michigan at Flint, Flint, Michigan 48502*
[7]*University of California-Davis, Davis, California 95616*
[8]*University of Delhi, Delhi 11 00 07, India*
[9]*Michigan State University, East Lansing, Michigan 48824*
[10]*Northeastern University, Boston, Massachusetts 02115*
[11]*Pennsylvania State University, University Park, Pennsylvania 16802*
[12]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[13]*University of Rochester, Rochester, New York 14627*
(Received 29 April 1994)

We report on a sample of J/ψ mesons coming from secondary vertices, a characteristic of heavy-quark decay, detected in the Fermilab Meson West spectrometer. Based on eight signal events in which a J/ψ emerges from a secondary vertex occurring in an air-gap region, we obtain an inclusive $b\bar{b}$ cross section of $75 \pm 31 \pm 26$ nb/nucleon. This result is compared to recent QCD predictions. We have also observed several events in the exclusive decay modes $B^{\pm} \to J/\psi + K^{\pm}$ and $B^0 \to J/\psi + K^{0*}$ in which the B mass is fully reconstructed.

PACS numbers: 13.85.Ni, 12.38.Qk, 13.25.Hw, 25.80.Ls

Next-to-leading order (NLO) calculations for the production of heavy quarks have become available during the past few years [1–3]. Recent collider data have shown that these predictions underestimate bottom production [4]. The calculations require the convolution of hard-scattering cross sections with parton distribution functions, and uncertainties result from the choice of gluon distribution functions, scale factors, and b-quark mass. Calculations by Berger [2] and by Mangano, Nason, and Ridolfi (MNR) [3] also provide predictions at fixed-target energies. Consequently, our measurement of the $b\bar{b}$ cross section for 515 GeV/c incident pions provides an opportunity to test these NLO QCD calculations.

In this Letter, we report on a measurement of the cross section for $\pi^- + \text{Be} \to b + X$, with $b \to J/\psi + X$ and $J/\psi \to \mu^+\mu^-$. $b \to J/\psi + X$ decays are uniquely tagged by J/ψ's emerging from secondary vertices. Although the branching ratio into J/ψ is small (1.3%) [5], this decay is advantageous since the resulting dimuons provide a clean trigger and signal. A significant background to secondary-vertex J/ψ's from b decays is, however, produced by events in which a high-momentum particle from the primary collision interacts further downstream in the target and produces a J/ψ (secondary interactions).

The experiment was carried out in the Fermilab Meson West beamline, using a large-aperture, open-geometry spectrometer with the capability of studying high-mass muon pairs. The muon detector, located 20 m downstream of the target, consisted of two muon proportional-wire-chamber (PWC) stations, a beam dump, a toroid magnet with an average p_T impulse of 1.3 GeV/c, four more muon PWC stations separated by iron and concrete shielding, and two muon hodoscopes [6]. The upstream part of the spectrometer consisted of 16 planes of silicon-strip detectors (SSDs), a dipole magnet with a p_T impulse of 0.45 GeV/c, 16 planes of PWCs and 16 planes of straw drift tubes, a liquid-argon calorimeter, and a forward calorimeter [7]. Dimuon pretriggers required coincidences between interaction counter and muon hodoscope signals. A fast processor triggered on the effective mass of track combinations in the muon PWCs. Data were collected during the 1990 run with a 515 GeV/c π^- beam incident on Be and Cu targets.

Figure 1 shows the opposite-sign dimuon invariant-mass distribution in the J/ψ region for muons linked through the entire detector. A fit yields $12\,640 \pm 150$ J/ψ's, with a mass resolution of 68 MeV/c and 387 ± 79 $\psi(2S)$'s. The J/ψ mass from the fit is 3.097 ± 0.001 GeV/c^2. To increase the efficiency and precision for finding a secondary vertex, the origin of the J/ψ was found by a muon-oriented vertex refitting procedure. Opposite-sign muon pairs in the mass range $2.85 < M_{\mu\mu} < 3.35$ GeV/c^2 with consistent intersections in the x-z and y-z planes were fitted with simultaneous vertex and J/ψ mass constraints. The resulting vertex served as a seed for an iterative vertex-fitting procedure which associated other tracks to this vertex. This procedure increased the secondary J/ψ vertex finding efficiency by 26%. The average vertex resolution was 14 and 350 μm in the transverse and longitudinal directions, respectively [8]. The reconstructed J/ψ vertex z-position distribution for these events is shown in Fig. 2(a).

The dimuon sample was searched for events in which the J/ψ vertex was downstream of the primary vertex, yielding 857 events. To clean the sample, several cuts were applied. Only events with at least three tracks from the primary were kept, yielding 631 events. Fiducial-volume cuts for both primary and secondary vertices passed 577 events. A significance greater than 3 was required for both the longitudinal and transverse separation between the primary and secondary vertices, with significance defined as the separation divided by the combined vertex uncertainty. An absolute longitudinal separation of 2.5 mm was required, leaving 121 events. Secondary J/ψ vertices with more than four associated hadrons were discarded to reduce the background from secondary interactions; 73 events passed this cut. The primary- and secondary-vertex z-position distributions for these events are shown in Figs. 2(b) and 2(c). In several events, the secondary J/ψ vertex occurs in an air-gap region; the background from secondary interactions is negligible for such events. The positions in the y-z plane of the J/ψ vertices in these gaps are shown in Fig. 3 (with z error bars). In ten events, the J/ψ vertex is at least 3 standard deviations away from the Be targets.

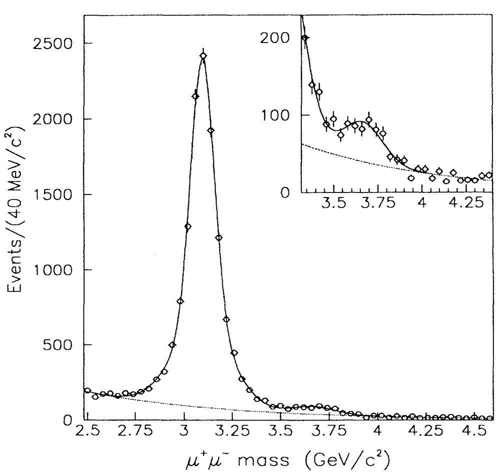

FIG. 1. The invariant mass distribution of $\mu^+\mu^-$ pairs. The solid curve is a fit to the data; the dashed curve shows the background contribution.

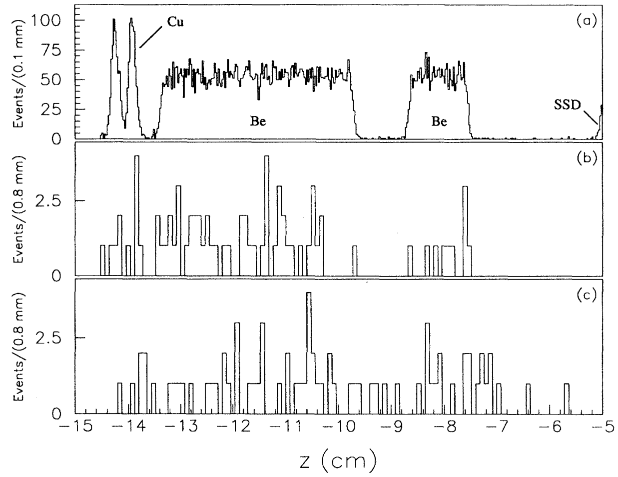

FIG. 2. Vertex z-coordinate distributions: (a) all refit J/ψ's, (b) primary vertex for the 73 events passing the cuts described in the text, (c) secondary J/ψ vertex for these events.

The background to this signal from false vertex reconstruction was estimated using Monte Carlo simulation of direct J/ψ production. This was a GEANT-based, full-detector simulation that included detector noise as observed in the data. The Monte Carlo events agree with our direct J/ψ data in terms of hit and track multiplicities, as well as position and momentum resolutions. These events were subject to the same analysis and cuts as used to obtain the secondary-vertex sample, yielding a 8.5×10^{-4} probability for a fake secondary-vertex J/ψ event. Normalizing to the observed number of J/ψ's gives a background of 11 ± 2 events to the 73-event sample. The corresponding background to the 10 air gap events is 2 ± 1 events. Additional contributions to the background were checked by searching the data itself for (i) dimuons with mass in the J/ψ sidebands from secondary vertices in the gap regions (no events were found), and (ii) reconstructed J/ψ vertices upstream of the primary vertex passing all cuts (1 event was found, consistent with Monte Carlo expectations). From these

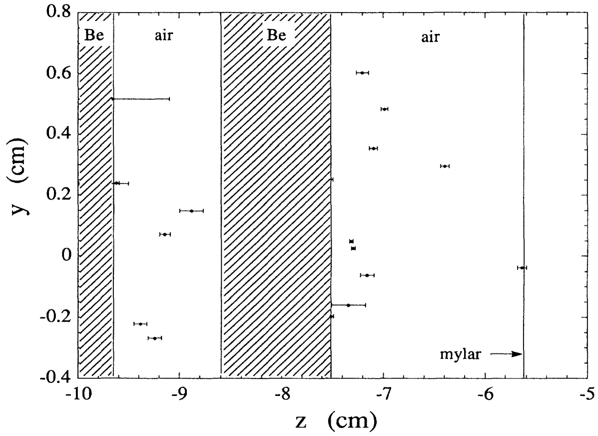

FIG. 3. J/ψ secondary vertex positions in the y-z plane showing events in the gap between target elements.

considerations, we obtain a background subtracted signal (attributed to b decays) of 8 $\pm$ 3.3 secondary-vertex J/ψ events in which the secondary vertex occurs in a region where only air is present.

The number of J/ψ's from b decays in the entire fiducial volume can be estimated from the number in the gaps. Monte Carlo studies indicate the (37 $\pm$ 5)% of the reconstructed vertices from b's produced in Be occur in the gap regions. Thus, 22 $\pm$ 10 $b \to J/\psi + X$ events are expected from Be. An additional 4 b events are expected from Cu. Even though the requirement of low multiplicity from the secondary vertex suppresses secondary interactions as a source for these J/ψ's, a simulation using the forward pion momentum spectrum from interacting beam events and the J/ψ production cross section indicates that 33 $\pm$ 6 of the events in the secondary-vertex sample are attributable to secondary interactions. Thus based on the observed gap events, combined with the Monte Carlo analysis, we expect 22 b's produced in Be, 4 b's produced in Cu, 33 secondary interaction events, and 11 events from false vertex reconstruction, for a total of 70 secondary vertex J/ψ events. This is consistent with the 73 events observed.

We searched the 73-event sample of secondary J/ψ's for the exclusive channels $B^{\pm} \to J/\psi + K^{\pm}$ and $B^0 \to J/\psi + K^{0*}$. Events with three-prong secondaries (2 muons plus another track) were selected as candidate $B^{\pm} \to J/\psi + K^{\pm}$ decays. To reduce background, only combinations with a secondary hadron having $p_T >$ 0.5 GeV/c were considered. This track was assumed to be a kaon, and its momentum was added to that of the J/ψ to form a candidate B momentum vector. The vector was projected back from the secondary to the primary vertex, and a transverse impact parameter δ_v was calculated; only events with $\delta_v < 80$ μm were kept [9]. Since tracks from the underlying event can be coincidentally associated with a secondary vertex, 4–prong secondary vertices were also included in the selection. The secondary vertices for these events were refit, omitting the low p_T track, and the events were analyzed under the hypothesis of 3-prong B decays. Four events survived the above cuts. In the search for neutral B decays, K^{0*}'s were observed by their decays into $K^{\pm}\pi^{\pm}$ pairs. Kaon mass was assigned only to tracks with momentum greater than half that of the other track, and pairs having mass consistent with the K^{0*} were combined with the J/ψ in the same manner as in the $B^{\pm}$ analysis. Momentum vectors of B^0 candidates were required to satisfy $\delta_v < 100$ μm. Five events passed these cuts (none had double $K\pi$ combinations).

The combined $J/\psi + K^{\pm}$ and $J/\psi + K^{0*}$ invariant-mass distribution is shown in Fig. 4. The expected B mass resolution is 35 MeV/c^2. There are 5 events near the nominal B-meson mass. A background analysis using primary-vertex events subject to the same cuts as the B-candidate sample shows no evidence for arbitrary enhancement in the B-mass region due to the imposed cuts. The 5 events have the following characteristics: 3 are $J/\psi\, K^{0*}$ candidates, 2 are $J/\psi\, K^{\pm}$; one $J/\psi\, K^{0*}$ event has its primary vertex in Cu while the rest of the events are from Be, and only 1 of the events has its secondary vertex in the air-gap region. Because of the small number of events observed in each decay mode, the exclusive decays are not used for a cross section determination.

Based on the background subtracted signal of 8 $b \to J/\psi + X$ air-gap events (and using J/ψ production as normalization), the $b\bar{b}$ cross section is given by

$$\sigma_{b\bar{b}} = \frac{N_{b\to\psi}}{\varepsilon_{b\to\psi} a_{b\to\psi} 2B(b \to \psi \to \mu^+\mu^-)} \times \left[\frac{\sigma_\psi B(\psi \to \mu^+\mu^-)}{A} \frac{\varepsilon_\psi a_\psi}{N_\psi} \right], \qquad (1)$$

where $\varepsilon_{b\to\psi}$ and ε_ψ are reconstruction efficiencies, $a_{b\to\psi}$ and a_ψ are detector acceptances, and A is the target atomic

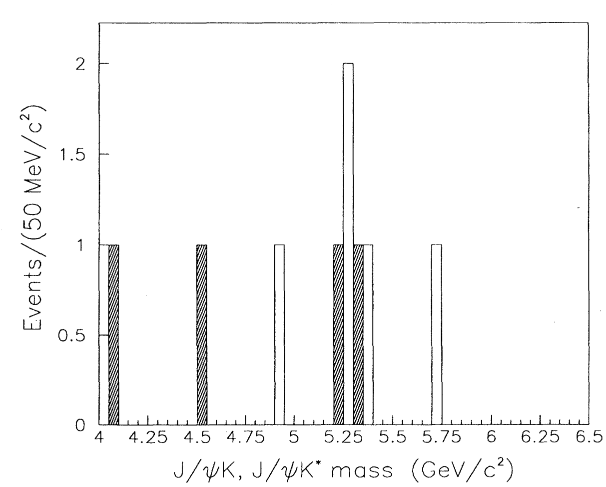

FIG. 4. Combined $J/\psi + K^{\pm}$ and $J/\psi + K^{0*}$ invariant-mass distribution; the hatched entries are $J/\psi\, K^{\pm}$ combinations.

mass. The factor of 2 arises since either the b or the $\bar{b}$ in an event can result in a J/ψ. We use a combined branching ratio of $B(b \to J/\psi \to \mu^+\mu^-) = 7.7 \times 10^{-4}$ [5,10], which is averaged over all b-hadron species, including baryons.

There are $N_\psi = 9800 \pm 130$ J/ψ's from the Be target having $x_F(\psi) > 0.1$ in the sample. The reconstruction efficiency and acceptance for these J/ψ's are $\varepsilon_\psi = 64\%$ and $a_\psi = 43\%$. We measure a J/ψ cross section (on Be) of $\sigma_\psi B(\psi \to \mu^+\mu^-)/A = 9.2 \pm 1.2$ nb/nucleon for $x_F(\psi) > 0.1$.

To determine detection efficiencies, bottom hadron pairs were generated according to the NLO calculations of MNR [3], with hadron momentum equal to that of the parent quark as observed in charm meson production [11]. One of the b hadrons in each event was randomly chosen to decay into $J/\psi + X$ with $J/\psi \to \mu^+\mu^-$. Our apparatus was found to accept only events in which the parent b quark had $x_F > 0$. The overall acceptance in this region is $a_{b\to\psi} = 19\%$. The reconstruction efficiency for $b \to J/\psi + X$ events of 39%, combined with a 27% probability of a decay occurring in an air-gap region yields an effective efficiency $\varepsilon_{b\to\psi} = 15\%$.

Using these values and $N_{b\to\psi} = 8 \pm 3.3$, we obtain a bottom cross section for $x_F > 0$ of $\sigma_{b\bar{b}} = 47 \pm 19 \pm 14$ nb/nucleon (assuming A^1 dependence) for π^--nucleon collisions at 515 GeV/c, where the first uncertainty is statistical and the second is systematic. The main sources of systematic uncertainty are in the normalization (13%), branching ratios (13%), b production, hadronization, decay properties (16%), and reconstruction efficiencies (18%). For comparison with theory and other experiments, this measurement is extrapolated from $x_F > 0$ to all x_F. Based on predictions by MNR [3], we obtain a total cross section of $\sigma_{b\bar{b}} = 75 \pm 31 \pm 26$ nb/nucleon. Extrapolations based on x_F distributions from Berger's predictions [2] and a measurement by Fermilab experiment E653 [12] are reflected in the quoted systematic uncertainty. With this cross section value we expect a total of 3 or 4 exclusive decays in the $J/\psi K^\pm$ and $J/\psi K^{0*}$ modes, which is consistent with the observed excess in Fig. 4.

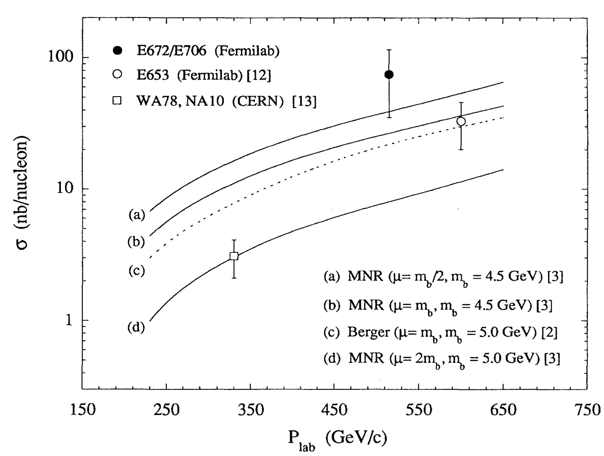

FIG. 5. Total bottom cross sections in π-nucleon collisions, compared with several theoretical predictions. Uncertainties on measurements represent statistical and systematic contributions added in quadrature.

A comparison of our measurement to predictions for bottom cross sections in π-nucleon collisions made by MNR [3] and Berger [2], and to those of previous experiments [12,13], is shown in Fig. 5. Our measurement favors predictions with smaller b-quark mass values and renormalization scales that are a smaller fraction of the mass scale. This is consistent with recent analysis of collider bottom-quark data [14].

We acknowledge the efforts of Fermilab's staff, and thank MNR for their assistance. This work was supported by the U.S. Department of Energy, the National Science Foundation, and the USSR State Committee for Utilization of Atomic Energy.

*Deceased.

[1] P. Nason, S. Dawson, and R.K. Ellis, Nucl. Phys. **B303**, 607 (1988); **B327**, 49 (1989); **B335**, 260 (1990).
[2] E.L. Berger, Phys. Rev. D **37**, 1810 (1988); Report No. ANL-HEP-CP-88-26 (1988).
[3] M. Mangano, P. Nason, and G. Ridolfi, Nucl. Phys. **B405**, 507 (1993); **B373**, 295 (1992).
[4] F. Abe *et al.*, Phys. Rev. Lett. **71**, 50 (1993).
[5] O. Adriani *et al.*, Phys. Lett. B **288**, 412 (1992).
[6] V. Abramov *et al.*, Report No. FERMILAB-PUB-91/62-E (1991); S. Kartik *et al.*, Phys. Rev. D **41**, 1 (1990).
[7] G. Alverson *et al.*, Phys. Rev. D **48**, 5 (1993).
[8] R. Jesik, Ph.D. thesis, University of Illinois at Chicago, 1993 (unpublished).
[9] The cuts employed in the exclusive decay analysis were derived from extensive Monte Carlo studies described in Ref. [8].
[10] D. Coffman *et al.*, Phys. Rev. Lett. **68**, 282 (1992).
[11] J. Appel, Annu. Rev. Nucl. Part. Sci. **42**, 367 (1992).
[12] K. Kodama *et al.*, Phys. Lett. **B303**, 359 (1993).
[13] M. Catanesi *et al.*, Phys. Lett **B187**, 431 (1987); P. Bordalo *et al.*, Z. Phys. C **39**, 7 (1988); M. Catanesi *et al.*, Report No. CERN-EP/89-118.
[14] M. Mangano *et al.*, Nuc. Instrum. Methods Phys. Res., Sect. A **333**, 57 (1993); E.L. Berger *et al.*, Phys. Rev. D **27**, 1895 (1992).