Mass and lifetime measurements of bottom and charm baryons in \( p\bar{p} \) collisions at \( \sqrt{s} = 1.96 \) TeV

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We report on mass and lifetime measurements of several ground state charmed and bottom baryons, using a data sample corresponding to 9.6 fb$^{-1}$ from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, and recorded with the Collider Detector at Fermilab. Baryon candidates are reconstructed from data collected with an online event selection designed for the collection of long-lifetime heavy-flavor decay products and a second event selection designed to collect $J/\psi \to \mu^+ \mu^-$ candidates. First evidence for the process $\Omega^- \to \Omega^0 \pi^-$ is presented with a significance of $3.3\sigma$. We measure the following baryon masses:

\[
M(\Xi^0_c) = 2470.85 \pm 0.24\text{(stat)} \pm 0.55\text{(syst)} \text{ MeV}/c^2, \\
M(\Xi^+_c) = 2468.00 \pm 0.18\text{(stat)} \pm 0.51\text{(syst)} \text{ MeV}/c^2, \\
M(\Lambda^0_b) = 5620.15 \pm 0.31\text{(stat)} \pm 0.47\text{(syst)} \text{ MeV}/c^2, \\
M(\Xi^-_b) = 5793.4 \pm 1.8\text{(stat)} \pm 0.7\text{(syst)} \text{ MeV}/c^2, \\
M(\Xi^0_b) = 5788.7 \pm 4.3\text{(stat)} \pm 1.4\text{(syst)} \text{ MeV}/c^2, \quad \text{and} \\
M(\Omega^-_b) = 6047.5 \pm 3.8\text{(stat)} \pm 0.6\text{(syst)} \text{ MeV}/c^2.
\]

The isospin splitting of the $\Xi^0_{c,b}$ states is found to be $M(\Xi^-_c) - M(\Xi^0_c) = 4.7 \pm 4.7\text{(stat)} \pm 0.7\text{(syst)} \text{ MeV}/c^2$. The isospin splitting of the $\Xi^{0,+}_{c,b}$ states is found to be $M(\Xi^0_c) - M(\Xi^+_c) = 2.8 \pm 0.3\text{(stat)} \pm 0.04\text{(syst)} \text{ MeV}/c^2$. The following lifetime measurements are made:

\[
\tau(\Lambda_b) = 1.565 \pm 0.035\text{(stat)} \pm 0.020\text{(syst)} \text{ ps}, \\
\tau(\Xi^+_c) = 1.32 \pm 0.14\text{(stat)} \pm 0.02\text{(syst)} \text{ ps}, \\
\tau(\Omega^-_b) = 1.66^{+0.53}_{-0.40}\text{(stat)} \pm 0.02\text{(syst)} \text{ ps}.
\]

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I. INTRODUCTION

The quark model describes the spectroscopy of hadrons with great success. In particular, this has been the case for the $D$ and $B$ mesons, where all of the ground states have been observed $^1$. The spectroscopy of $c$ baryons also agrees well with the quark model, and a rich spectrum of baryons containing $b$ quarks is predicted $^{2,3}$. The accumulation of large data sets from the Tevatron and Large Hadron Collider has made possible the observation and measurements of most of the $b$-baryon ground states.
states containing a single heavy quark \(4\,10\) and several resonant states \(3\,11\,13\). The samples of most \(b\) baryons accumulated to date are small, and the measurements of the properties of these particles are limited by the sample size. The exception to this is the \(\Lambda_b\) baryon, where the reconstructed samples are now large enough to probe its properties with precision. Early measurements of the \(\Lambda_b\) lifetime disagreed with predictions from heavy-quark expansion theory, if compared with the \(B^0\) lifetime \(14\). With the large samples that are now available, precision measurements of the \(\Lambda_b\) lifetime are providing a strong test of the heavy-quark expansion in describing its properties since limited by the sample size. In Sec. IV, we present measurements of the \(\Lambda_b\) lifetime \(15\). In this paper, we report the measurements of mass and lifetime, \(\tau\), for the \(\Lambda_b\), \(\Xi_b^-\) and \(\Omega_b^-\) baryons through the decay processes \(\Lambda_b \rightarrow J/\psi \Lambda, \Xi_b^- \rightarrow J/\psi \Xi^-,\) and \(\Omega_b^- \rightarrow J/\psi \Omega^-\). Mass measurements of the \(\Xi_b^0, \Xi_b^+, \Xi_b^0,\) and \(\Xi_b^0\) are made by reconstructing the processes \(\Xi_b^0 \rightarrow \Xi^- \pi^+, \Xi_b^+ \rightarrow \Xi^- \pi^0 \pi^+, \Xi_b^0 \rightarrow \Xi^- \pi^-\), and \(\Xi_b^0 \rightarrow \Xi^- \pi^-\). In addition, we report first evidence for the process \(\Omega_b^- \rightarrow \Omega^0 \pi^-, \Omega_b^+ \rightarrow \Omega^- \pi^+,\) and \(\Lambda \rightarrow p \pi^-.\) Charge conjugate modes are implicitly included. These measurements are made in \(p\overline{p}\) collisions at a center-of-mass energy of 1.96 TeV using the Collider Detector at Fermilab (CDF II), corresponding to an integrated luminosity of 9.6 fb\(^{-1}\). This paper uses the full CDF II data set collected during the 2001-11 operation of the Tevatron.

The strategy of this analysis is to calibrate and check the measurement technique on the better known \(b\)-meson states and then to extend the method to property measurements of the \(b\) baryons reconstructed from the same data. All mass and lifetime measurements are performed on the \(B^+ \rightarrow J/\psi K^+ \) and \(B^0 \rightarrow J/\psi K^* \) \((892)^0\), \(K^* \) \((892)^0 \rightarrow K^- \pi^-\) final states to provide a large sample for comparison to the world-average values. The decay mode \(B^0 \rightarrow J/\psi K_S^0, K_S^0 \rightarrow \pi^+ \pi^-\) is also used as a reference process. Although its sample size is smaller than the samples of \(B^+\) and other \(B^0\) decays, this is an appropriate reference because the \(K_S^0\) is reconstructed from charged particles that are significantly displaced from the collision, similar to the final-state particles from the \(b\)-baryon decays studied in this work.

We begin with a brief description of the detector and its simulation in Sec. II. In Sec. III we present measurements of the properties of the \(\Xi_b^0, \Lambda_b, \Xi_b^0,\) and \(\Omega_b^-\) baryons, which include particle masses and lifetimes. We conclude in Sec. IV with a summary of the results.

II. DETECTOR DESCRIPTION AND SIMULATION

The CDF II detector has been described in detail elsewhere [16]. This analysis primarily relies upon the charged-particle tracking and muon-identification systems. The tracking system consists of four different detector subsystems that operate inside a 1.4 T solenoid with its axis parallel to the beamline. The first of these is a single layer of silicon strip detectors (L00) at a radius of 1.35 – 1.6 cm from the axis of the solenoid. It measures charged-particle positions (hits) in the transverse view with respect to the beam, which is parallel to the \(z\) direction. A five-layer silicon detector (SVX II), surrounding L00 measures hits at radii of 2.5 to 10.6 cm [17]. Each of these layers provides a transverse measurement and a stereo measurement of \(90^\circ\) (three layers) or \(\pm 1.2^\circ\) (two layers) with respect to the beam direction. The outermost silicon detector lies between 19 cm and 30 cm radially, and provides one or two hits, depending on the track pseudorapidity (\(N\)), where \(N = -\ln[\tan(\theta/2)]\), with \(\theta\) being the angle between the particle momentum and the proton-beam direction. An open-cell drift chamber (COT) completes the tracking system, and covers the radial region from 43 cm to 132 cm [18]. The COT consists of 96 sense-wire layers, arranged in 8 superlayers of 12 wires each. Four of these superlayers provide axial measurements and four provide stereo views of \(\pm 2^\circ\). Transverse momentum, \(p_T\), (defined as the component of the particle momentum perpendicular to the proton-beam direction) of charged particles is measured in the COT with a resolution of \(\sigma(p_T)/p_T = 0.0017 [\text{GeV/c}]^{-1}\).

Electromagnetic and hadronic calorimeters surround the solenoid coil. Muon candidates from the decay \(J/\psi \rightarrow \mu^+ \mu^-\) are identified by two sets of drift chambers located radially outside the calorimeters. The central muon chambers cover the region \(|\eta| < 0.6\), and detect muons with \(p_T > 1.4 \text{ GeV/c}\) [19]. A second muon system covers the region \(0.6 < |\eta| < 1.0\) and detects muons with \(p_T > 2.0 \text{ GeV/c}\). Muon selection is based on matching the measurements from these chambers to COT tracks, both in projected position and angle.

The analysis presented here is based on events recorded with two different online event-selection (trigger) algorithms. The first is dedicated to the collection of a \(J/\psi \rightarrow \mu^+ \mu^-\) sample. The first level of the three-level trigger system requires two muon candidates with matching tracks in the COT and muon chambers. The second level imposes the requirement that muon candidates have opposite electric charge and limits the accepted range of azimuthal opening angle. The highest level of the \(J/\psi\) trigger reconstructs the muon pair in software, and requires the invariant mass of the pair to fall within the range \(2.7 – 4.0 \text{ GeV/c}^2\).

The second data set used is triggered by a system designed to collect particle candidates that decay with lifetimes characteristic of heavy flavor hadrons. The first level of this trigger requires two charged particles in the COT with \(p_T > 2.0 \text{ GeV/c}\). In the second level of this second trigger, the silicon vertex trigger [20] is used to associate SVX II data with the tracks found in the COT to precisely measure the impact parameter (defined as the distance of closest approach in the transverse view) with...
respect to the beamline. The impact parameter resolution (typically 40 \mu m) for these tracks allows the isolation of a track sample that does not originate directly from the p\bar{p} collision. The silicon vertex trigger requires two tracks with impact parameters d in the range 0.1 – 1.0 mm with respect to the beam and a point of intersection at least 200 \mu m from the beamline in the transverse view. These and other requirements bias the trigger efficiency toward candidates that have a long decay time. Lifetime measurements made with these data therefore require a careful study of these biases and appropriate corrections. The additional statistical power from lifetime measurements that use these data is insufficient to overcome the systematic uncertainty due to the trigger conditions. Therefore, only mass measurements are extracted from the hadronic trigger data in this work.

The mass resolution and acceptance for the b hadrons used in this analysis are studied with a Monte Carlo simulation that generates b hadrons consistent with CDF measurements of p_T and rapidity distributions. The final-state decay processes are simulated with the EvtGen \cite{baldit97} program, and all simulated b hadrons are produced without polarization. The generated events are input to the detector and trigger simulation based on a GEANT3 description \cite{allison} and processed through the same reconstruction and analysis algorithms that are used for the data.

III. PARTICLE RECONSTRUCTION METHODS

A. J/\psi reconstruction

The analysis of the data obtained with the muon trigger begins with a selection of well-measured J/\psi \rightarrow \mu^+\mu^- candidates. The trigger requirements are confirmed by selecting events that contain two oppositely charged muon candidates, each with matching COT and muon-chamber tracks. Both muon tracks are required to have associated position measurements in at least three layers of the SVX II. This data sample provides approximately 6.5 \times 10^7 J/\psi candidates, measured with an average mass resolution of approximately 20 MeV/c^2. These candidates are required to have a two-track invariant mass within the range listed in Table I.

B. Neutral Hadron Reconstruction

The reconstruction of K_S^0, K*(892)^0, and \Lambda candidates uses all particles with p_T > 0.4 GeV/c found in the COT that are not associated with muons used in the J/\psi reconstruction or tracks used by the hadronic trigger. Pairs of oppositely charged particles are combined to identify these neutral decay candidates. Silicon detector information is not used on these to avoid decay-length-dependent biases on the reconstruction efficiency due to the long lifetimes of the particles. Candidate selection for these neutral states is based upon the mass calculated for each track pair, which is required to fall within the ranges given in Table I after the appropriate mass assignment is made for each track. Backgrounds to the K_S^0 (c\tau \approx 2.7 cm) and \Lambda (c\tau \approx 7.9 cm) signals \cite{pons05} are reduced by imposing requirements on the transverse flight-distance, given for neutral particles as f(h) \equiv (r^2_t - r^2_a)/p_T(h)/|p_T(h)|, where p_T(h) is the transverse momentum of the hadron candidate, and r^2_t, r^2_a are the transverse positions of the decay point and point of origin, respectively. The transverse flight-distance of the K_S^0 and \Lambda candidates with respect to the primary vertex (defined as the beam position in the transverse view) is required to be greater than 1.0 cm.

| Resonance (final state) | Mass range (MeV/c^2) |
|-------------------------|----------------------|
| J/\psi (\mu^+\mu^-)     | \pm 80               |
| K*(892)^0 (K^+\pi^-)    | \pm 30               |
| K_S^0 (\pi^+\pi^-)      | \pm 20               |
| \Lambda (p\pi^-)        | \pm 9                |
| \Xi^- (\Lambda\pi^-)    | \pm 9                |
| \Omega^- (\Lambda K^-)  | \pm 8                |
| \Xi^0 (\Xi^-\pi^+\pi^-) | \pm 30               |
| \Omega^0 (\Omega^-\pi^+\pi^-) | \pm 30 |

C. Charged Hyperon Reconstruction

For events that contain a \Lambda candidate, the remaining particles reconstructed in the COT, again without additional silicon information, are assigned the pion or kaon mass, and \Lambda \pi^- or \Lambda K^- combinations are identified that are consistent with the decay process \Xi^- \rightarrow \Lambda \pi^- or \Omega^- \rightarrow \Lambda K^- candidates are required to have a mass that is consistent with the ranges listed in Table I. Charged particles with p_T as low as 0.4 GeV/c are used for \Xi^- reconstruction. However, event simulation indicates that the p_T distribution of K^- mesons produced from \Omega^- decays has a higher average value, and declines more slowly, than the p_T distribution of the pions from \Lambda or \Xi^- decays. Therefore, p_T(K^-) > 1.0 GeV/c is required for the \Omega^- sample.

Several features of the track topology are used to reduce the \Xi^- and \Omega^- backgrounds. In order to improve the mass resolution for \Xi^- and \Omega^- candidates, the reconstruction requires a good fit of the three tracks that simultaneously constrains the \Lambda decay products to the \Lambda mass, and the \Lambda trajectory to intersect with the helix of the \pi^- (K^-) originating from the \Xi^- (\Omega^-) candidate. In addition, the transverse flight-distance of the \Lambda candidate with respect to the reconstructed decay vertex of
the $\Xi^-$($\Omega^-$) candidate is required to exceed 1.0 cm. Due
to the long lifetime of the $\Xi^-$ ($c\tau \approx 4.9$ cm) and $\Omega^-$
($c\tau \approx 2.5$ cm) particles [1], a transverse flight-distance of at least
1.0 cm (corresponding to a measurement uncertainty of approximately
one standard deviation for a typical candidate) with respect to the primary
vertex is required. Transverse flight-distance for charged particles
is defined as the arc length from the point of closest approach to
the origin to the decay point. Possible kinematic reflections are removed from the $\Omega^-$ sample by requiring
that the combinations in the sample fall outside the $\Xi^-$ mass range listed in Table II when the candidate
$K^-$ track is assigned the mass of the $\pi^-$. In instances
where the correct vertex assignment for the decay tracks is ambiguous, a fit is performed for all configurations and
a single, preferred candidate is chosen by retaining only the
fit combination with the lowest $\chi^2$.

D. Charmed Hyperon Reconstruction

The $\Xi^-$ and $\Omega^-$ candidates are used to reconstruct the
processes $\Xi^0 \rightarrow \Xi^- \pi^+$, $\Xi^+ \rightarrow \Xi^- \pi^+ \pi^+$, and
$\Omega^0 \rightarrow \Omega^- \pi^+$. Each $c$-baryon candidate is subjected to
a simultaneous fit of all the tracks in the decay process
that constrains the track intersections and decay product
momenta to be consistent with the appropriate decay topology. In addition, the tracks from the $\Lambda$ decay are
constrained to the known $\Lambda$ mass.

The kinematic properties of $\Xi^-$ and $\Omega^-$ decays and the lower $p_T$ limit of 0.4 GeV/c on the final-state tracks
cause the majority of accepted charged hyperon candidates to have $p_T > 1.5$ GeV/c. This fact, along with the
long lifetimes of the $\Xi^-$ and $\Omega^-$, results in a significant
fraction of hyperon candidates having decay vertices located
several centimeters radially outward from the beam position.
Therefore, we refine the charged-hyperon reconstruction by using the improved determination of its
trajectory available from tracking these particles in the silicon detector. The $\Xi^-$($\Omega^-$) point of origin, point of
decay, and momentum obtained from the full four- or five-track fit are used to define a helix that serves as the
seed for an algorithm that associates silicon detector hits with
the charged-hyperon track. Charged-hyperon candidates with track measurements in at least one layer
of the silicon detector have excellent impact parameter
resolution (average of 60 $\mu$m) for the charged hyperon
track.

Mass distributions are shown in Fig. 11 for all combinations and for the subset where the $\Xi^-$ or $\Omega^-$ track
reconstruction is improved by using at least one hit in the
SVX II and the impact parameter of the $c$ baryon
with respect to the beam is less than 100 $\mu$m. The
improvement in charmed-hyperon purity is evident. An es-
timate of the yield in each case is made by performing a
binned fit on these distributions, which models the data
with a Gaussian signal and linear background. Due to
the small sample size, the Gaussian width term for the
$\Omega^0$ is fixed at 8 MeV/$c^2$, which is the resolution predicted
by the event simulation. The background under each sig-
nal is estimated by integrating the background function
from the fit over the range $\pm 2\sigma$ around the signal mass,
where $\sigma$ is the characteristic width of the Gaussian signal.
Signal yields and purity, defined as signal-to-background
ratio, are listed in Table III for all fits. A requirement of

| State          | Full sample | Tracked in SVX II |
|----------------|-------------|-------------------|
|                | Yield       | Purity            |
| $\Xi^0$        | 5614 ± 247  | 0.15 ± 0.01       |
| $\Xi^+          | 7984 ± 354  | 0.11 ± 0.01       |
| $\Omega^0$     | 416 ± 135   | 0.03 ± 0.01       |

E. $b$ baryon reconstruction

A good fit is required on the final-state tracks of all $b$-
baryon candidates that constrains them to originate from
the vertices appropriate for the particular decay channel
being considered. In addition, we require $ct > 100 \mu$m
and $d < 100 \mu$m for each $b$-baryon candidate, to remove
prompt and poorly reconstructed candidates. All hadron
decay products used in the $b$-baryon reconstruction are
required to have a measured mass consistent with the
known values, according to the ranges listed in Table I.

Several selection criteria are used that are common to
all $b$-hadron candidates with a $J/\psi$ meson in the final
state. We require the transverse momentum of the $b$
hadron to exceed 6.0 GeV/c and $p_T(h) > 2.0$ GeV/c,
where $h$ is the hadron accompanying the $J/\psi$ meson.
These requirements reduce combinatorial background. In
addition, the final-state fit constrains the mass of the
$\mu^+ \mu^-$ pair to the known mass of the $J/\psi$ meson [1].
hadron tracks are reconstructed without silicon-detector information. Therefore, all b-hadron decay position information is derived solely from the muons, and the decay-time resolution is similar for all b hadrons in this data set.

The hadronic trigger data provides a sample of Ξb baryons through the decay channel Ξb → Ξc π−, Ξc → Ξ− π+ (π−), Ξ− → Λ π−, and Λ → p π−. A similar decay chain is used for Ωb− reconstruction. The final-state track fit used in these decay processes includes a constraint on the Λ decay products to the known Λ mass. The π− candidates from the b-hadron decay are required to have electric charge opposite to the Λ baryon number, and to be consistent with having satisfied the trigger by having pT > 2.0 GeV/c and d > 100 μm. The backgrounds under the Ξc states are also reduced by restricting the sample based on the measured decay time of the Ξc candidates to the range −2σt < t(Ξc) < 3σt(Ξc) + 2σt, where σt is the calculated uncertainty on the decay time and τ0(Ξc) is the known lifetime of the appropriate Ξc baryon.[1]

The lifetime of the Ω0 is so short (σt ≈ 21 μm)[1] that the tracking system has no ability to resolve it. Consequently, no t(Ω0) requirement is made in the selection of Ω0 π− combinations. Figure 2 shows Ω− π+ and Ω− π+ π− mass distributions of selected combinations. Figure 2(a) shows the distribution of all Ω− π+ combinations that, combined with a π− candidate, yield a mass within 50 MeV/c² of the Ω− mass previously measured by this experiment[8]. The known mass of the Ω0 is also indicated. The Ω− π+ combinations shown in Fig. 2(b) are chosen from two Ω− π+ π− mass sidebands, selected to be 50 MeV/c² in width and centered at ±100 MeV/c² from the Ω− mass. There is a clear indication of Ω0 candidates in events where the Ω− π+ π− mass is consistent with the Ω0 mass, whereas no enhancement compatible with an Ω0 signal appears in the background sample. A similar comparison is made between Figs. 2(c) and 2(d), where the Ω− π+ π− mass is shown for candidates consistent with Ω0 decays and candidates from the sidebands of the Ω− π+ mass distribution.

F. Evidence for the Ω− → Ω0 π− decay

The indication of an Ω− signal in the Ω0 π− mass distribution shown in Fig. 2(c) requires additional consideration. Because the process Ω− → Ω0 π− has never been observed, a standard significance test is performed where the mass distribution is fit once with a signal amplitude that is allowed to float and once where it is fixed to zero (the null hypothesis). The signal mass used is fixed and the measurement resolution is fixed to 20 MeV/c², as determined by the simulation. Two different Ω0 mass assumptions are used, corresponding to the value measured in this work, and the value recently measured by the LHCb Collaboration[10], in order to assess the sensitivity of the significance to the mass value. Twice the change in the logarithm of the fit likelihood between the null and floating signal hypotheses, 2Δ ln L, is found to be 10.3 and 13.3 for the different Ω0− mass assumptions.

The probability that the signal shown in Fig. 2(c) arises from a background fluctuation is obtained from a simple simulation of the distribution of ten independent mass values generated uniformly over the range used in Fig. 2(c). The generated unbinned distribution is then fit with the likelihood function twice, as is done with the data. The value of 2Δ ln L between the two fits is then recorded. The process is repeated 10⁴ times and values of 2Δ ln L = 10.3 or greater occurs with a frequency of 5.5 × 10⁻⁴. This corresponds to a single sided fluctuation of a Gaussian distribution of 3.3σ, corresponding to evidence for the process Ω− → Ω0 π−.

IV. PARTICLE PROPERTIES

The mass and lifetime of the b hadrons are measured by a fit with data binned in decay time, but not in mass[8]. The mass and signal yield in each ct bin are found by maximizing a likelihood given by

\[
\mathcal{L} = \prod_i N_i \prod_j [f_j P_i^s + (1 - f_j) P_{i,j}^b],
\]

where \(N_i\) is the number of ct bins chosen for the fit, \(f_j\) and \(f_j\) are the numbers of candidates and the signal fraction, respectively, for time bin \(j\), and \(P_i^s\) and \(P_{i,j}^b\) are the mass probability density functions for the signal and background, respectively, for candidate \(i\). The signal probability distribution is given by

\[
P_i^s = (1 - \alpha) G(m_i, m_0, s_0 \sigma_i m) + \alpha G(m_i, m_0, s_1 \sigma_i m),
\]

where \(G\) are Gaussians with average \(m_0\); \(m_i\) and \(\sigma_i m\) are the measured mass and uncertainty for candidate \(i\); and \(\alpha, s_0,\) and \(s_1\) are parameters determined in the fit that describe, respectively, the relative contribution from each Gaussian and possible deviations between the calculated and true mass uncertainty. The background is modeled as

\[
P_{i,j}^b = \sum_{n=0}^{n}\ a_{n,j} P_n(m_i),
\]

where \(P_n(m_i)\) are orthonormal polynomials of order \(n\), which are normalized over the range of the fit, and \(a_{n,j}\) are constants obtained in the fit. The background constants are obtained independently for each time range \(j\). The overall normalization is assured by fixing \(a_{0,j} = 1 - \sum_{n=1}^{2} a_{n,j}\).

The lifetime is determined by virtue of the fact that the fractional occupancy of each particular range of ct implies a specific lifetime for a particular measurement resolution. This is implemented in a two-step process,
which begins by maximizing the likelihood function in the mass distributions given in Eq. 1. In the second step, all parameters obtained in the mass fits are fixed and an additional lifetime term is added to the likelihood, rewriting it as

$$\mathcal{L} = \prod_j N_j \left[ f_j N_j / \sum_j f_j N_j, \sigma_j^b \right] \prod_i \left[ f_i \mathcal{P}_i^a + (1 - f_i) \mathcal{P}_i^b \right],$$

where $R_j = f_j N_j / \sum_j f_j N_j$, $\sigma_j^b$ is the uncertainty on $R_j$, and $w_j(\tau, \sigma_j)$ is the predicted fractional occupancy on each time range for lifetime $\tau$ measured with uncertainty $\sigma_j$. The predicted occupancy is found by integrating the decay-time distribution convolved with the decay-time-measurement resolution, which is assumed to be Gaussian and is calculated analytically. Decay-time bins are chosen to have approximately equal occupancy for the initial lifetime chosen for the fit. The highest bin has no upper bound.

There are several advantages to this technique over the usual method of simultaneously fitting the signal and background lifetimes. The only distribution where the usual method of simultaneously fitting the signal has no upper bound.

There are several advantages to this technique over the usual method of simultaneously fitting the signal and background lifetimes. The only distribution where the usual method of simultaneously fitting the signal has no upper bound.

$$\mathcal{P}_i^a = \left( 1 + \frac{\mathcal{P}_i^a}{\mathcal{P}_i^b} \right) \left( \frac{1}{\lambda_0} \right)^{\mathcal{P}_i^b / \mathcal{P}_i^a},$$

where $\lambda_0 = 1 / (\tau_0 b)$ and $\tau_0$ is the average decay time. The effect of reflections from the projected fit are shown in Fig. 4. Results from the mass fits are listed in Table IV and discussed in Sec. IV.C.

The approach to fitting the mass and lifetime of the $\Lambda_b$ candidates is identical to that used for the meson reference signals. The approach to fitting the mass and lifetime of the $\Lambda_b$ candidates is identical to that used for the meson reference signals. The approach to fitting the mass and lifetime of the $\Lambda_b$ candidates is identical to that used for the meson reference signals. The approach to fitting the mass and lifetime of the $\Lambda_b$ candidates is identical to that used for the meson reference signals. The approach to fitting the mass and lifetime of the $\Lambda_b$ candidates is identical to that used for the meson reference signals.

B. Masses of the $\Xi^0_c$ and $\Xi^+_c$ baryons

The large samples of $\Xi_c$ baryons in the full data set and the mass resolution available from the tracking system allow precise $\Xi_c$ baryon mass measurements. The masses are obtained using the unbinned likelihood fit applied to all candidates with $ct > 100\mu m$. The $\Xi_c^{-}\pi^+$ and $\Xi_c^{-}\pi^+\pi^-$ mass distributions along with projections of the fits are shown in Fig. 6. Results from the mass fits are listed in Table IV.

C. $\Lambda_b$ Measurements

The approach to fitting the mass and lifetime of the $\Lambda_b$ is identical to that used for the meson reference signals. The approach to fitting the mass and lifetime of the $\Lambda_b$ is identical to that used for the meson reference signals. The approach to fitting the mass and lifetime of the $\Lambda_b$ is identical to that used for the meson reference signals. The approach to fitting the mass and lifetime of the $\Lambda_b$ is identical to that used for the meson reference signals. The approach to fitting the mass and lifetime of the $\Lambda_b$ is identical to that used for the meson reference signals.
TABLE III: $B$ meson mass and $c\tau$ comparisons to known values\textsuperscript{[1]}. Results from the entire data set (total) and the subset not included in the world averages (new) are listed. Only statistical uncertainties are listed.

\begin{center}
\begin{tabular}{|c|c|c|c|}
\hline
Final state & Mass (MeV/$c^2$) & $c\tau$ ($\mu m$) & Yield \\
\hline
$J/\psi K^+$ (total) & 5278.75 ± 0.06 & −0.5 ± 0.2 & 489.0 ± 2.1 & 3.0 ± 3.0 \\
$J/\psi K^+$ (new) & 5278.74 ± 0.08 & −0.5 ± 0.2 & 491.9 ± 3.0 & 0.1 ± 3.8 \\
$J/\psi K^{0*}$ (total) & 5279.01 ± 0.11 & −0.5 ± 0.2 & 486.6 ± 3.3 & 3.2 ± 3.9 \\
$J/\psi K^{0*}$ (new) & 5278.95 ± 0.17 & −0.6 ± 0.2 & 485.4 ± 4.7 & 3.0 ± 5.1 \\
\hline
\end{tabular}
\end{center}

The systematic uncertainties on the mass measurements reported here are similar to those obtained for other $b$ hadrons in previous CDF II analyses. The mass scale uncertainty is taken from earlier work\textsuperscript{[23]}. Here, the $J/\psi$, $\psi(2S)$ and $\Upsilon$ decays, reconstructed in dimuon final states, were used to set the mass scale. The differences of the measured masses from the true masses are parametrized as functions of the total kinetic energy in these decays and are then used to obtain the mass scale uncertainties listed in Table VI. The effect of the mass-resolution model on the mass-uncertainty scale is tested by examining the $\Lambda_b$-baryon candidates whose $\Lambda$ decay point is outside the silicon system. A systematic shift of 0.05 – 0.1 MeV/$c^2$ of the mass of the $J/\psi \Omega^-$ and $\Omega_c^0$ $\pi^−$ combinations integrated in decay time and the projected fits are shown in Fig. 10. The time-dependent mass distributions and decay-time distribution for the $\Omega_c^0 \rightarrow J/\psi \Omega^-$ channel are shown in Fig. 11. The mass resolution terms $s_0$ are fixed to the values obtained in the analogous channels used in the $\Xi_b^-$ fits. The results of the mass and lifetime fits are listed in Table IV.

G. Systematic uncertainties

The mass distributions for the $J/\psi \Xi^-$ and $\Xi_c^0 \pi^−$ combinations integrated in decay time and the projected fits are shown in Fig. 7. The time-dependent mass distributions and decay-time distribution for the $\Xi_b^- \rightarrow J/\psi \Xi^-$ channel are shown in Fig. 8. Mass and lifetime results of the fits are listed in Table IV.

E. $\Xi_c^0$ measurements

The process $\Xi_c^0 \rightarrow J/\psi \Xi^0$ is expected to occur, in analogy to $\Xi_b^- \rightarrow J/\psi \Xi^-$. However, this process requires the accurate reconstruction of a low-momentum $\pi^0$, so it is outside the sensitivity of this experiment. Consequently, we are limited to a $\Xi_c^0$ mass measurement in the $\Xi_b^- \rightarrow \Xi_c^0 \pi^- \pi^−$ channel. The $\Xi_c^0 \pi^−$ mass distribution and the projection of the fit overlaid on the data are shown in Fig. 9 and the fit result is listed in Table IV.

F. $\Omega_c^-$ measurements

The approach of fitting the mass and lifetime of the $\Omega_c^-$ is identical to that used for the meson reference signals, with the exception that only three decay-time ranges are used in the lifetime calculation due to the small sample of candidates. The mass distributions for the $J/\psi \Omega^-$ and $\Omega_c^0 \pi^−$ combinations integrated in decay time and the projected fits are shown in Fig. 10. The time-dependent mass distributions and decay-time distribution for the $\Omega_c^0 \rightarrow J/\psi \Omega^-$ channel are shown in Fig. 11. The mass resolution terms $s_0$ are fixed to the values obtained in the analogous channels used in the $\Xi_b^-$ fits. The results of the mass and lifetime fits are listed in Table IV.
quadrature to obtain the total systematic uncertainties.

The $B$ mesons reconstructed in the $J/\psi$ sample serve as a precision reference sample to support the evaluation of the systematic uncertainties. The mass and lifetime results obtained for the $B^+$ and $B^0$ are listed in Table III. Comparisons between the measurements and the known values are listed. The known values contain contributions from a subset of the CDF Run II data. Consequently, values are given for the full data set and the data taken since the previous measurement. We find the more recent data to be completely consistent with our earlier measurements, indicating that no significant degradation of the tracking resolution occurred. A comparison of the results in reference signals with the known values demonstrates that the mass measurements are well understood.

The masses of the $\Xi^+_b$ and $\Omega^+_b$ baryons are each measured in two different final states. The mass results are combined to provide a single measurement following Ref. [27]. These combined results, and the mass results for the other baryons, are listed in Table VI. The momentum scale uncertainty cancels in measurements of the mass differences between the $\Xi^+_c$ and $\Xi^+_b$, and the $\Xi^0_b$ and $\Xi^0_c$ baryons. The estimates for these isospin splittings are also listed in Table VI.

The lifetime fit is repeated on the reference signals to determine the sensitivity of the technique to the input parameters chosen for the fit. The decay-time uncertainty $\sigma_{\text{t}}$ is shown in Fig. 12 for the $B^0 \to J/\psi K_S^0$ sample, where the background contribution is removed by subtracting mass sideband uncertainties. If this uncertainty is varied between 15 and 45 $\mu$m, the results of the lifetime fit are found to have a relative variation of less than $10^{-3}$. Variations in the number of decay-time bins have similar impact.

Systematic uncertainties on the lifetime measurements of the $b$ baryons are identical to those of the $B$ mesons. The $B$ meson reference signals all have lifetime results that are within 1% of their known values, as shown in Table III. If we use only the recent data for the $B^0 \to J/\psi K_S^0$ process, we find complete consistency with the known lifetime within $\pm 6 \mu$m, or 1.3%. This is taken as the systematic uncertainty for all $b$-baryon lifetime measurements.

V. FINAL RESULTS

Final results for the properties of the $b$ baryons are listed in Tables VI and VII. The measurements of the masses of the $\Xi_b$ baryons are competitive with the world averages, and consistent with them. The isospin splitting of the states is also comparable to the world average. These measurements serve to improve our overall knowledge of heavy baryon dynamics. Theoretical calculations of the $\Xi_b$ baryon masses are not as precise as the current measurements, so these results serve to constrain the models considered for heavy baryon mass predictions.

VI. CONCLUSIONS

In conclusion, the CDF Run II data set is analyzed to identify the largest possible low-background sample of $\Xi_c$ and $b$-baryon ground states. The mass and lifetime properties of these particles are measured, and the results compared to precisely measured quantities for $B$ mesons obtained in similar final states. The mass and isospin splitting of the $\Xi_c$ system are measured with precisions that are comparable to the world averages. The first evidence for the process $\Omega^0_b \to \Omega^0_c \pi^-$ is shown. The masses and lifetimes of the $\Lambda_b$, $\Xi^0_b$ and $\Omega^0_b$ baryons are measured and are found consistent with LHCb determinations [11]. The isospin splitting of the $\Xi_b$ system is unique to this experiment and is updated with the final data set. These results supersede previous measurements, which were obtained using a subset of these data.

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TABLE V: Contributions to the systematic uncertainty on the mass measurements.

| Source                  | Uncertainty (MeV/c^2) |
|-------------------------|-----------------------|
| Ξ^0                     | Ξ^+                   |
| B^0                     | Λ_b                   | Ξ_b                 | Ξ_b^-               | Ω^-_b               |
| J/ψ K^0 S               | J/ψ ω^0             | J/ψ Ξ^0             | J/ψ Ξ^-^0          | J/ψ Ω^-^0           |
| Mom. scale              | 0.35 0.35            | 0.42 0.42           | 0.40 0.40          | 0.50 0.40           | 0.40 0.55 |
| Reso. model             | 0.05 0.05            | 0.1 0.1             | 0.1 0.1            | 0.1 0.1             | 0.1 0.1 |
| Material                | 0.38 0.38            | 0.0 0.25            | 0.21 0.47          | 1.16 1.15           | 0.38 0.94 |
| Total                   | 0.55 0.51            | 0.43 0.53           | 0.47 0.6           | 1.4 1.4             | 0.6 1.2 |

TABLE VI: Ξ_c and b-baryon mass results. The first uncertainty listed is statistical and the second is systematic.

| Baryon | Mass (MeV/c^2) |
|--------|----------------|
| Ξ^0_c  | 2470.85 ± 0.24 ± 0.55 |
| Ξ^+ c  | 2468.00 ± 0.18 ± 0.51 |
| Λ_b    | 5620.15 ± 0.31 ± 0.47 |
| Ξ^- b  | 5793.4 ± 1.8 ± 0.7 |
| Ξ^0 b  | 5788.7 ± 4.3 ± 1.4 |
| Ω^- b  | 6047.5 ± 3.8 ± 0.6 |

M(Ξ^0_c) - M(Ξ^+ c) = 2.85 ± 0.30 ± 0.04
M(Ξ^- b) - M(Ξ^0 b) = 4.7 ± 4.7 ± 0.7

TABLE VII: b-baryon lifetime results. The first uncertainty listed is statistical and the second is systematic.

| Baryon | Lifetime (ps) |
|--------|---------------|
| Λ_b    | 1.565 ± 0.035 ± 0.020 |
| Ξ^- b  | 1.36 ± 0.15 ± 0.02 |
| Ω^- b  | 1.66±0.53      ± 0.49 |

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FIG. 1: Distribution of $\Xi^{-}\pi^{+}$ mass for (a) all candidates and (b) the subset where the $\Xi^{-}$ is tracked in the silicon detector and the impact parameter with respect to the beamline is less than 100 $\mu$m. Panels (c,d) and (e,f) show similar distributions for $\Xi^{-}\pi^{+}\pi^{+}$ and $\Omega^{-}\pi^{+}$ candidates, respectively.
FIG. 2: Distribution of $\Omega^- \pi^+$ (a,b) and $\Omega^- \pi^+ \pi^-$ (c,d) mass for candidates obtained from the $\Omega_\nu$ selection. Panel (a) shows the $\Omega^- \pi^+$ mass for candidates consistent with the $\Omega_\nu \rightarrow \Omega^- \pi^+ \pi^-$ signal region; panel (b) shows the $\Omega^- \pi^+$ mass for candidates restricted to the $\Omega_\nu$ mass sidebands. Panel (c) shows the $\Omega^- \pi^+ \pi^-$ mass for candidates consistent with the $\Omega_\nu^c \rightarrow \Omega^- \pi^+ \pi^-$ signal region; panel (d) shows the $\Omega^- \pi^+ \pi^-$ mass for candidates restricted to the $\Omega_\nu^c$ mass sidebands.
FIG. 3: Distributions of (a) $J/\psi K_S^0$ mass and (b) $ct$ for $B^0$ reconstructed in the $B^0 \rightarrow J/\psi K_S^0$ decay. The mass and lifetime fits are overlaid in dashed red. For display purposes, the upper limit of the $ct$ distribution is chosen to be 0.135 cm so that the displayed distribution contains 95% of the candidates, based on the initial lifetime estimate.
FIG. 4: Distribution of (a) $\Xi^-\pi^+$ and (b) $\Xi^-\pi^+\pi^+$ mass used for the $\Xi_c$ mass measurements. The fits are overlaid on the data in dashed red.

FIG. 5: Distribution of $J/\psi$ mass used for the $\Lambda_b$ mass measurement. The fit is overlaid on the data in dashed red.
FIG. 6: Distribution of (a) \( J/\psi \Lambda \) mass divided into four independent decay-time ranges and (b) \( ct \) of \( \Lambda_b \) candidates used to calculate the lifetime. The fits are overlaid on the data in dashed red.
FIG. 7: Distribution of (a) the $J/\psi \Xi^-$ and (b) $\Xi_c^0 \pi^-$ mass used for the $\Xi_b^-$ mass measurements. The fits are overlaid on the data in dashed red.
FIG. 8: Distribution of (a) $J/\psi \Xi^-$ mass divided into four independent decay-time ranges and (b) $ct$ of $\Xi_c^-$ candidates used to calculate the lifetime. The fits are overlaid on the data in dashed red.

FIG. 9: Distribution of $\Xi_c^+ \pi^-$ mass used for the $\Xi_c^0$ mass measurement. The fit is overlaid on the data in dashed red.
FIG. 10: Distribution of (a) $J/\psi \Omega^-$ and (b) $\Omega_c^0 \pi^-$ mass used for the $\Omega_c^-$ mass measurement. The fits are overlaid on the data in dashed red.
FIG. 11: Distribution of (a) $J/\psi\Omega^-\bar{\Omega}$ mass divided into three independent decay-time ranges and (b) $ct$ of $\Omega^-\bar{\Omega}$ candidates used to calculate the lifetime. The fits are overlaid on the data in dashed red.

FIG. 12: Distribution of $\sigma_{ct}$ for (a) $B^0 \rightarrow J/\psi K^0_s$ candidates and (b) $\Lambda_b \rightarrow J/\psi \Lambda$ candidates.