Observation and Mass Measurement of the Baryon Ξ_b^-

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We report the observation and measurement of the mass of the bottom, strange baryon Ξ_b^- through the decay chain $\Xi_b^- \to J/\psi\, \Xi^-$, where $J/\psi \to \mu^+ \mu^-$, $\Xi^- \to \Lambda\, \pi^-$, and $\Lambda \to p\, \pi^-$. Evidence for observation is based on a signal whose probability of arising from the estimated background is 6.6×10^{-15}, or 7.7 Gaussian standard deviations. The Ξ_b^- mass is measured to be 5792.9 ± 2.5 (stat.) ± 1.7 (syst.) MeV/c^2.

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Since its inception, the quark model has had great success in describing the spectroscopy of hadrons. Extension of the quark model into the sector of hadrons containing the b quark has proven successful for the 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]. However, direct observation of b baryons has been limited to a single state, the Λ_b (quark

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content udb) [1], until recently. Evidence for b baryons that also contain a strange quark was shown from LEP [3] through partial reconstruction of decays containing electrons and muons. Recent results from the Tevatron on the Σ_b states (quark content uub, ddb) [4] and Ξ_b^- (quark content dsb) [5] are beginning to subject the b baryons to closer examination.

In this Letter, we report on the observation of a heavy baryon and measurement of its mass. The decay properties of this state are consistent with the weak decay of a b baryon, and we interpret our result as the observation of the Ξ_b^- baryon. These events were observed in $p\overline{p}$ collisions at a center of mass energy of 1.96 TeV using the Collider Detector at Fermilab (CDF II), through the decay chain $\Xi_b^- \rightarrow J/\psi\,\Xi^-$, where $J/\psi \rightarrow \mu^+\mu^-$, $\Xi^- \rightarrow \Lambda\,\pi^-$, and $\Lambda \rightarrow p\,\pi^-$. Charge conjugate modes are included implicitly. This measurement is based on a data sample with an integrated luminosity of 1.9 fb^{-1}.

The CDF II detector has been described in detail elsewhere [6]. This analysis primarily relies upon the tracking and muon identification systems. The tracking system consists of a silicon microstrip detector and an open-cell drift chamber (COT) that operate inside a solenoid with a 1.4 T magnetic field. Muon candidates from the decay $J/\psi \rightarrow \mu^+\mu^-$ are identified by two sets of drift chambers located radially outside the electromagnetic and hadronic calorimeters. The central muon chambers cover the pseudorapidity region $|\eta| < 0.6$ [7], and are sensitive to muons with transverse momentum $p_T > 1.4$ GeV/c. A second muon system covers the region $0.6 < |\eta| < 1.0$ and detects muons having $p_T > 2.0$ GeV/c. This analysis is based on events recorded with a trigger that 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 chamber systems. The second level imposes the requirement that muon candidates have opposite charge and limits the accepted range of opening angle. The highest level of the J/ψ trigger reconstructs the muon pair in software, and requires that the invariant mass of the pair fall within the range $2.7 - 4.0$ GeV/c^2.

The analysis of the data 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. We also require that both muon tracks have associated measurements in at least three layers of the silicon detector and a two-track invariant mass within 80 MeV/c^2 of the world-average J/ψ mass [1]. This data sample provides approximately 15 million events containing J/ψ candidates.

The reconstruction of Ξ^- candidates begins with a scan of all additional tracks found in each selected J/ψ event. Pairs of oppositely charged tracks are considered Λ decay candidates by assigning the proton (pion) mass to the track with the higher (lower) momentum. This mass assignment is always correct for Λ candidates within the acceptance of the experiment because of the $\approx$200 MeV/c transverse momentum cutoff of the tracking system. All intersecting pairs of tracks with an invariant mass within 10 MeV/c^2 of the world average Λ mass [1] have their track parameters recalculated according to a fit where the momenta of the two tracks are constrained to form the Λ invariant mass. The decay vertex is used to calculate the Λ displacement from the beam-line in the direction of the track pair's transverse momentum. The background due to tracks originating from the primary vertex is reduced by requiring this displacement to exceed 1.0 cm. For candidates that satisfy these requirements, the remaining tracks are assigned the pion mass, and are examined for $\Lambda\,\pi^-$ combinations that are consistent with the decay process $\Xi^- \rightarrow \Lambda\,\pi^-$. In order to obtain the best possible $\Lambda\,\pi^-$ mass resolution, the reconstruction uses a fit on the three tracks that simultaneously constrains the Λ decay products to the accepted Λ mass, and the Λ trajectory to intersect with the helix of the Ξ^- decay pion. For all Ξ^- candidates, the reconstructed decay position of the Λ candidate is required to be radially displaced at least 1 cm with respect to the reconstructed decay vertex of the Ξ^- candidate.

The majority of Ξ^- candidates have $p_T > 1.5$ GeV/c. This, along with the long lifetime of the Ξ^- ($c\tau = 4.9$ cm) [1], results in a significant fraction of the Ξ^- candidates having decay vertices located several centimeters radially outward from the beam-line. Therefore, we are able to refine the Ξ^- reconstruction by making use of the improved determination of the trajectory that can be obtained by tracking the Ξ^- in the silicon detector. The Ξ^- candidates have an additional fit performed on the three tracks that simultaneously constrains both the Λ and Ξ^- masses of the appropriate track combinations, and provides the best possible estimate of the Ξ^- momentum and decay position. The result of this fit is used to define a helix that serves as the seed for an algorithm that searches for silicon detector hits associated with the Ξ^- track. We retain for further analysis all Ξ^- candidates with two or more axial silicon detector hits. This technique provides excellent impact parameter resolution for the Ξ^- track (average of 60 μm), and has been used previously [8]. The $\Lambda\,\pi^-$ invariant mass spectrum of all combinations that satisfy these requirements is shown in Fig. 1. Approximately 23,500 Ξ^- candidates above the combinatorial background are identified. The Ξ_b^- search includes the subset of these combinations with an invariant mass within 10 MeV/c^2 of the world average Ξ^- mass [1].

The mass resolution for the $J/\psi\,\Xi^-$ final state is studied with a Monte Carlo simulation that generates b quarks according to a next-to-leading-order calculation [9], and produces Ξ_b^- events by simulating Peterson fragmentation [10] on the b quark-level distributions. The decay $\Xi_b^- \rightarrow J/\psi\,\Xi^-$ is simulated with EvtGen [11]. These events are used as input to the detector and trigger simulations based on a GEANT3 description [12]. These simulated events are then processed through the same reconstruction and analysis algorithms used for the data. Analysis of the simulated Ξ_b^- events shows that a 10% improvement in mass resolution can be obtained if the momenta of the Ξ^- decay products are allowed to vary in the fit of the Ξ_b^- candidate, rather than simply using the Ξ^- track. Consequently, a procedure that simultaneously fits the five tracks of the final state, constrains the three vertices of the decay chain to the appropriate topology, and constrains the masses of the J/ψ, Ξ^-, and Λ to their world average masses, is used to provide the best estimate of $J/\psi\,\Xi^-$ mass. The estimate for the Ξ_b^- mass resolution is found to be approximately 15 MeV/c^2. In particular, we note that the $J/\psi\,\Xi^-$ invariant mass resolution is comparable to the mass resolution obtained with the CDF II detector for other B hadrons with a J/ψ in the final state [13].

The selection used to isolate the $\Xi_b^- \to J/\psi\,\Xi^-$ decay process is guided by the properties of other B hadrons that include a J/ψ in the final state. The important properties include the lifetime of the ground-state B hadrons and the energy available in the decay. First, the $B^\pm, B^0$, and B_s mesons and Λ_b baryon, all appear to have lifetimes dominated by the weak decay of the b quark. We expect the same to hold true for the Ξ_b^- and for its lifetime to be comparable to these states. Second, these particles all decay to final states $J/\psi\,X$, where X is a single hadron. In these decays the momentum carried by the decay products in the rest frame of the B hadron falls in the fairly narrow range of $1570 - 1744$ MeV/c^2 for decays where lightest decay products are considered. We expect the energy released in the decay of the Ξ_b^- to be comparable. This expectation is also consistent with the range of theoretical predictions ($5788-5812$ MeV/c^2) for the Ξ_b^- mass [2]. Consequently, we have chosen a Ξ_b^- search strategy that will provide an optimal sensitivity for a final state that shares similar properties with these well-established B hadrons.

We have developed the event selection by studying $B^\pm \to J/\psi\,K^\pm$ decays. This final state is identified by assigning the $K^\pm$ mass to all tracks not used in the J/ψ reconstruction. Each three-track combination must satisfy a fit where the tracks are required to originate from a common vertex and the invariant mass of the muon pair is constrained to the world average J/ψ mass [1]. Approximately 30,000 $B^\pm$ candidates are identified in this sample. Several characteristics of the final state are used as selection requirements to obtain a $B^\pm$ signal with very little background. Minimum transverse momentum requirements on the $K^\pm$ and $B^\pm$ candidates are used to suppress backgrounds from the event that are not related to the $B^\pm$ decay. The trajectory of the $K^\pm$ is required to originate from the $B^\pm$ decay vertex by placing a requirement on its impact parameter $d_{SV}(K)$ and associated uncertainty $\sigma_{d_{SV}}(K)$ with respect to the vertex found in the J/ψ fit and on those $d_{PV}(K)$ and $\sigma_{d_{PV}}(K)$ measured with respect to the primary vertex. Reasonable vertex quality is assured by placing a minimum value on the accepted probability $P(\chi^2)$ of the mass- and vertex-constrained fit used to obtain the $B^\pm$ candidate. We suppress the promptly-produced combinatorial background by rejecting candidates with low proper decay time, $t \equiv \vec{L_T} \cdot \vec{p_T}(B) \frac{M(B)}{|p_T(B)|^2}$, where $M(B)$ is the mass of the $B^\pm$ candidate, $\vec{p_T}(B)$ is the transverse momentum of the $B^\pm$ candidate, and $\vec{L_T}$ is the transverse displacement of the $B^\pm$ decay vertex from the beam-line. A requirement on proper decay time uncertainty σ_t removes poorly-reconstructed combinations. We also reject combinations that are inconsistent with having originated from the beam-line by requiring a small magnitude of the impact of the $B^\pm$ candidate, $\vec{d}_{PV}(B) \equiv \vec{L_T} \times \vec{p_T}(B)/|p_T(B)|$, and a small angle β between $\vec{L_T}$ and $\vec{p_T}(B)$.

This analysis uses a two-step selection procedure. Final selection criteria are listed in Table I. We first impose the "standard" selection requirements listed there and retain all $J/\psi\,\Xi^-$ combinations that satisfy them. Any combination that fails only one of the "standard" selection requirements is also allowed into the final sample if it satisfies both of the p_T requirements of the "high-p_T" selection requirements and fails no more than one of the other requirements in this set. The combination of "standard" and "high-p_T" requirements reduce the background in the $B^\pm \to J/\psi\,K^\pm$ sample to approximately 400 combinations, while retaining a signal of 16,000 $B^\pm$ candidates.

As is done for the reconstruction of the $B^\pm$, the treatment of the $J/\psi\,\Xi^-$ candidates requires a mass- and vertex-constrained fit on the muon candidates and the Ξ^- track. The selection criteria of Table I are placed on the $J/\psi\,\Xi^-$ sample where we simply exchange K^- for Ξ^- and $B^\pm$ for Ξ_b^- where appropriate. Combinations that satisfy these requirements form the final set of Ξ_b^- candidates. The invariant mass of this sample is calculated through the full five-track fit and is shown in Fig. 2.

TABLE I: Selection variables and requirements for the "standard" selection and "high-p_T" selection as described in the text. Here "K" refers to the third track combined with the J/ψ and is a $K^\pm$ or Ξ^- candidate for the $B^\pm$ or Ξ_b^- candidates, respectively. Similarly, "B" refers to either $B^\pm$ or Ξ_b^-, as is appropriate.

Selection variable	Standard	High-p_T
$p_T(K)$	> 1.7 GeV/c	> 2.5 GeV/c
$p_T(B)$	> 5 GeV/c	> 6 GeV/c
$\|d_{SV}(K)\|$	$< 100\ \mu$m	$< 80\ \mu$m
$\|d_{PV}(K)\|/\sigma_{d_{PV}(K)}$	> 2.5	> 3
$P(\chi^2)$	$> 0.1\%$	$> 1\%$
$\|d_{PV}(B)\|$	$< 75\ \mu$m	$< 60\ \mu$m
ct	$> 80\ \mu$m	$> 100\ \mu$m
$c\sigma_t$	$< 30\ \mu$m	$< 25\ \mu$m
β	< 0.4 radians	< 0.3 radians

The mass resolution estimate implies that the majority of the candidates of a Ξ_b^- signal will fall in an invariant mass bin with a width of 75 MeV/c^2. The data shown in Fig. 2 contain 18 candidates in the 75 MeV/c^2 range of $5750-5825$ MeV/c^2. We model the combinatoric background by considering candidates in the range $5700-6500$ MeV/c^2; the data yield 23 candidates in this range. No events contribute multiple candidates. The upper limit of this range is chosen arbitrarily, and has no impact on the result. The lower limit is chosen to avoid partially reconstructed $\Xi_b^{-,0} \rightarrow J/\psi\,\Xi^- X$ decays, where X represents additional undetected particles. We assume that the mass distribution of the combinatorial background is uniform and that the occupancy due to background combinations of any particular 75 MeV/c^2 mass bin within the 800 MeV/c^2 search range can be described by a binomial distribution, with a single event probability given by the ratio of the two mass ranges used. The probability of the observed occupancy in the $5750-5825$ MeV/c^2 mass range is therefore estimated as a binomial probability of 18 or more events from a sample of 23 total occurences and a single event probability of 75/800. The probability of 18 events occuring in the $5750-5825$ MeV/c^2 mass range due to a random fluctuation of the background is found to be 6.6×10^{-15}, equivalent to a 7.7σ variation from a Gaussian distribution. Consequently, we interpret the data distribution shown in Fig. 2 to be the observation of the production of a resonance, with a width consistent with the detector resolution.

The masses and their uncertainties obtained from the five-track final state fit method are used in an unbinned likelihood fit to measure the Ξ_b^- mass. The negative log-likelihood to minimize has the form

$$\mathcal{L} = -\sum_{i=1}^{N} \log\left[fG(m_i, m_0, s_m\sigma_i^m) + (1-f)\mathcal{C}\right], \quad (1)$$

where m_i is the mass obtained for a single candidate, σ_i^m is the uncertainty on that mass, $G(m_i, m_0, s_m\sigma_i^m)$ is a Gaussian distribution with average m_0 and characteristic width $s_m\sigma_i^m$, and $\mathcal{C}$ is a constant background term. The quantities obtained from the fitting procedure include f, the fraction of the events found in the signal, m_0, the best average mass, and s_m, a scale factor on the mass uncertainty which accounts for a possible shift in the mass uncertainty. This procedure yields a best estimate for the Ξ_b^- mass of 5792.9 ± 2.5 MeV/c^2. The uncertainty scale factor is determined to be 2.0 ± 0.4. The signal fraction is calculated to be 0.76 ± 0.09, giving a yield of 17.5 ± 4.3 Ξ_b^- candidates in this data sample.

Several systematic effects have been considered for their impact on the Ξ_b^- mass measurement. The overall momentum scale of the tracking system is established by calibrating with the well-measured J/ψ, $\psi(2S)$, and Υ states [13]. The momentum scale uncertainty contributes a systematic uncertainty of ±0.4 MeV/c^2 on the Ξ_b^- mass measurement. Alignment and material distribution of the tracking system contributes an additional ±0.6 MeV/c^2 of uncertainty. The method requires knowledge of the mass of the final state Ξ^-, a quantity that is known to ±0.13 MeV/c^2 [1]. The mass uncertainty of the J/ψ is included in the momentum scale calibration, and the mass uncertainty of the Λ (±0.006 MeV/c^2) is negligible for this analysis. Finally, the largest systematic variation seen on the mass measurement occurs when alternative fitting models are used for the mass calculation. The signal distribution has been fit with a single Gaussian where its parameters are allowed to vary in the fit. A double Gaussian is also used, where the widths are fixed to values obtained in simulation, and only the average mass is allowed to vary. These different models for the probability distribution function of the signal create variations of ±1.5 MeV/c^2 on the mass result. A summary of the systematic uncertainties is listed in Table II. They are combined in quadrature to obtain an overall systematic uncertainty of ±1.7 MeV/c^2 on the Ξ_b^- mass measurement.

TABLE II: Systematic uncertainties on the Ξ_b^- mass measurement.

Effect	Uncertainty (MeV/c^2)
Momentum scale	±0.40
Tracking alignment and material	±0.60
Ξ^- mass	±0.13
Fit model	±1.5
Total	±1.7

In conclusion, we use the CDF II detector at the Tevatron to observe the Ξ_b^- in $p\bar{p}$ collisions with an integrated luminosity of 1.9 fb^{-1}. A signal with 17.5 ± 4.3 Ξ_b^- candidates and a significance of 7.7σ is seen in the decay channel $\Xi_b^- \rightarrow J/\psi\,\Xi^-$. The mass of this baryon is measured to be 5792.9 ± 2.5 (stat.) ±1.7 (syst.) MeV/c^2. This result is consistent with theoretical expectations [2]. The mass measurement presented is also consistent with the only other direct observation of this state [5], and represents a significant improvement in precision.

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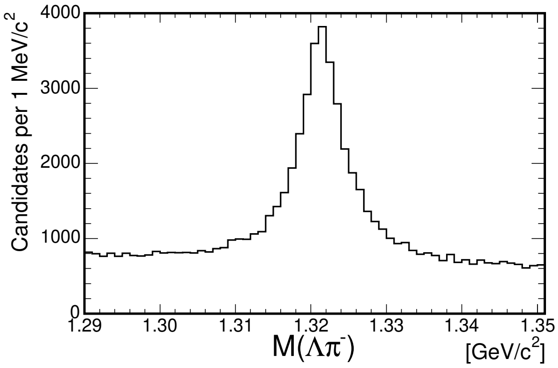

FIG. 1: The invariant mass distribution of $\Lambda\,\pi^-$ combinations having an associated track in the silicon detector in events containing J/ψ candidates.

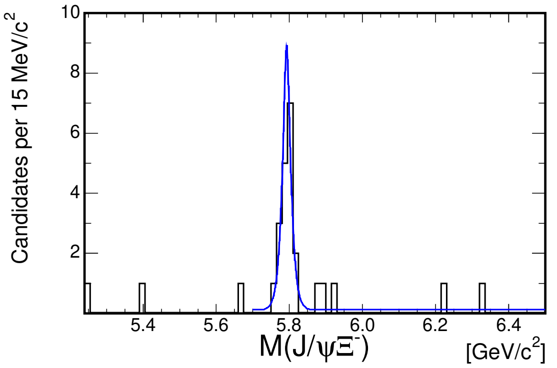

FIG. 2: The $J/\psi\,\Xi^-$ invariant mass distribution for combinations that satisfy the selection requirements. The projection of the likelihood function is overlaid on the data.