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Observation of the Ω_b^- and Measurement of the Properties of the Ξ_b^- and Ω_b^- Baryons at CDF

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We report the observation of the bottom, doubly-strange baryon Ω_b^- through the decay chain $\Omega_b^- \to J/\psi\,\Omega^-$, where $J/\psi \to \mu^+\mu^-$, $\Omega^- \to \Lambda K^-$, and $\Lambda \to p\pi^-$, using 4.2 fb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, and recorded with the Collider Detector at Fermilab. A signal is observed whose probability of arising from a background fluctuation is 4.0×10^{-8}, or 5.5 Gaussian standard deviations. The Ω_b^- mass is measured to be $6054.4 \pm 6.8(\text{stat.}) \pm 0.9(\text{syst.})$ MeV/c^2. The lifetime of the Ω_b^- baryon is measured to be $1.13^{+0.53}_{-0.40}(\text{stat.}) \pm 0.02(\text{syst.})$ ps. In addition, for the Ξ_b^- baryon we measure a mass of $5790.9 \pm 2.6(\text{stat.}) \pm 0.8(\text{syst.})$ MeV/c^2 and a lifetime of $1.56^{+0.27}_{-0.25}(\text{stat.}) \pm 0.02(\text{syst.})$ ps. Under the assumption that the Ξ_b^- and Ω_b^- are produced with similar kinematic distributions to the Λ_b^0 baryon, we find $\frac{\sigma(\Xi_b^-)\mathscr{B}(\Xi_b^- \to J/\psi\,\Xi^-)}{\sigma(\Lambda_b^0)\mathscr{B}(\Lambda_b^0 \to J/\psi\,\Lambda)} = 0.167^{+0.037}_{-0.025}(\text{stat.}) \pm 0.012(\text{syst.})$ and $\frac{\sigma(\Omega_b^-)\mathscr{B}(\Omega_b^- \to J/\psi\,\Omega^-)}{\sigma(\Lambda_b^0)\mathscr{B}(\Lambda_b^0 \to J/\psi\,\Lambda)} = 0.045^{+0.017}_{-0.012}(\text{stat.}) \pm 0.004(\text{syst.})$ for baryons produced with transverse momentum in the range of $6 - 20$ GeV/c.

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1. Introduction

In this paper, we report the observation of a heavy baryon and the measurement of its mass, lifetime, and relative production rate compared to the Λ_b^0 production [1]. The decay properties of this state are consistent with the weak decay of a b-baryon. We interpret our result as the observation of the Ω_b^- baryon ($|ssb\rangle$).

This Ω_b^- observation is made 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 $\Omega_b^- \to J/\psi\,\Omega^-$, where $J/\psi \to \mu^+\mu^-$, $\Omega^- \to \Lambda K^-$, and $\Lambda \to p\pi^-$. Charge conjugate modes are included implicitly. Mass, lifetime, and production rate measurements are also reported for the Ξ_b^-, through the similar decay chain $\Xi_b^- \to J/\psi\,\Xi^-$, where $J/\psi \to \mu^+\mu^-$, $\Xi^- \to \Lambda\pi^-$, and $\Lambda \to p\pi^-$. The production rates of both the Ξ_b^- and Ω_b^- are measured with respect to the Λ_b^0, which is observed through the decay chain $\Lambda_b^0 \to J/\psi\,\Lambda$, where $J/\psi \to \mu^+\mu^-$, and $\Lambda \to p\pi^-$. These measurements are based on a data sample corresponding to an integrated luminosity of 4.2 fb^{-1}.

The strategy of the analysis presented here is to demonstrate the reconstruction and property measurements of the Ξ_b^- and Ω_b^- as natural extensions of measurements that can be made on better known $b-$hadron states obtained in the same data. All measurements made here are performed on the $B^0 \to J/\psi\,K^*(892)^0$, $K^*(892)^0 \to K^+\pi^-$ final state, to provide a large sample for comparison to other measurements. The decay modes $B^0 \to J/\psi\,K_s^0$, $K_s^0 \to \pi^+\pi^-$ and Λ_b^0 are also used as reference processes.

2. Particle Reconstruction Methods

The analysis presented here is based on events recorded with a trigger that is dedicated to the collection of a $J/\psi \to \mu^+\mu^-$ sample. The analysis of the data begins with a selection of well-measured $J/\psi \to \mu^+\mu^-$ candidates. This data sample provides approximately 2.9×10^7 J/ψ candidates, measured with an average mass resolution of ~ 20 MeV/c^2.

The reconstruction of K_s^0, $K^*(892)^0$, and Λ candidates uses all tracks with $p_T > 0.4$ GeV/c that are not associated with muons in the J/ψ reconstruction. Candidate selection for these neutral states is based upon the mass calculated for each oppositely charged track pair, which is required to fall within ±30, ±20, and ±9 MeV/c^2 of the nominal mass for the $K^*(892)^0$, K_s^0, and Λ, respectively. Backgrounds to the K_s^0 and Λ are reduced by requiring the flight distance of the K_s^0 and Λ with respect to the primary vertex to be greater than 1.0 cm. Approximately 3.6×10^6 Λ candidates are found with with $p_T(\Lambda) > 2.0$ GeV/c.

For events that contain a Λ candidate, the remaining tracks are assigned the pion or kaon mass, and $\Lambda\pi^-$ or ΛK^- combinations are identified that are consistent with the decay process $\Xi^- \to \Lambda\pi^-$ or $\Omega^- \to \Lambda K^-$. $p_T(K^-) > 1.0$ GeV/c is required for our Ω^- sample, which reduces the combinatorial background by 60%, while reducing the Ω^- signal predicted by our Monte Carlo simulation by 25%. In addition, the flight distance of the Λ candidates with respect to the reconstructed decay vertex of the $\Xi^-(\Omega^-)$, and the flight distance from the primary vertex of the Ξ^- and Ω^- candidates is required to exceed 1.0 cm. Kinematic reflections are removed from the Ω^- sample by requiring that the combinations consistent with Ξ^- decay, when the candidate K^- track is assigned the mass of the π^-. Any ambiguities for the proper track assignments of the hadrons are resolved examining the $P(\chi^2)$ of the vertex fits. Approximately 41 000 Ξ^- and 3500 Ω^- candidates are found in this data sample. $\Lambda\pi^-$ or ΛK^- combinations within ± 9 and ± 8 MeV/c^2 of the nominal Ξ^- and Ω^- masses are selected for b-hadron reconstruction.

The reconstruction of b-hadron candidates uses the same method for each of the states reconstructed for this analysis. The K and hyperon candidates are combined with the J/ψ candidates by fitting the full four-track or five-track state with constraints appropriate for each decay topology and intermediate hadron state. Specifically, the $\mu^+\mu^-$ mass is constrained to the nominal J/ψ mass [2], and the neutral K or hyperon candidate is constrained to originate from the J/ψ decay vertex. In addition, the fits that include the charged hyperons constrain the Λ candidate tracks to the nominal Λ mass [2], and the Ξ^- and Ω^- candidates to their respective nominal masses [2]. For our final sample, b-hadron candidates are required to have $p_T > 6.0$ GeV/c and the neutral K or hyperon to have $p_T > 2.0$ GeV/c. The promptly-produced combinatorial background is suppressed by rejecting candidates with low proper decay time, and spurious combinations are rejected by placing a requirement on the final state impact with respect to the beamline.

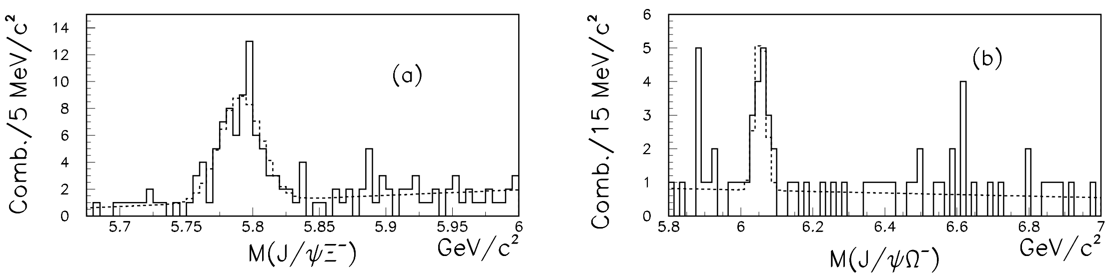

Figure 1: The invariant mass distributions of (a) $J/\psi\,\Xi^-$ and (b) $J/\psi\,\Omega^-$ combinations for candidates with $ct > 100\,\mu$m. The projections of the unbinned mass fit are indicated by the dashed histograms.

3. Observation of the Decay $\Omega_b^- \to J/\psi\,\Omega^-$

The $J/\psi\,\Omega^-$ mass distribution with $ct > 100\,\mu$m is shown in Fig. 1b. The significance of the structure seen in the $J/\psi\,\Omega^-$ mass distribution is evaluated with a simultaneous fit to mass and lifetime information which is maximized for two different conditions. The first maximization allows all parameters to vary in the fit. The second calculation fixes the signal fraction to 0.0. The value of $-2\ln\mathscr{L}$ obtained for the null hypothesis is higher than the value obtained for the fully varying calculation by 37.3 units. We interpret this as equivalent to a χ^2 with three degrees of freedom, which has a probability of occurrence of 4.0×10^{-8}, or a 5.5σ fluctuation. Consequently, we interpret the $J/\psi\,\Omega^-$ mass distributions shown in Fig. 1b to be the observation of a weakly decaying resonance, with a width consistent with the detector resolution. We treat this resonance as observation of the Ω_b^- baryon through the decay process $\Omega_b^- \to J/\psi\,\Omega^-$.

4. Ξ_b^- and Ω_b^- Property Measurements

To reduce the background to b-hadrons due to prompt production, a $ct > 100\,\mu$m requirement is placed on all candidates for inclusion in the mass measurements. The mass distributions of the

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candidates are shown in Fig. 1, along with projections of the fit function. The results of this fit are listed in Table 1. Systematic uncertainties for the Ξ_b^- and Ω_b^- masses are largely driven by our B^0 mass measurements, and are estimated to be 0.8 and 0.9 MeV/c^2, respectively.

The lifetime of b-hadrons is measured in this analysis by a technique that is insensitive to the detailed lifetime characteristics of the background. This allows a lifetime calculation to be performed on a relatively small sample, since a large number of events is not needed for a background model to be developed. The data are binned in ct, and the number of signal candidates in each ct bin is compared to the value that is expected for a particle with a given lifetime and measurement resolution. The estimates of the systematic uncertainties are obtained from the the B^0 lifetime measurements. The results of the fits for the lifetimes of the baryons and reference samples are listed in Table 1.

A further goal of this analysis is to measure the production rates of the Ξ_b^- and Ω_b^-, relative to the more plentiful Λ_b^0, where we measure ratios of cross section times branching fractions. The acceptances and efficiencies of the three baryons states are obtained as a function of p_T from the simulation of the detector. We use the observed p_T distribution of Λ_b^0 production to obtain the total efficiency for the Ξ_b^- and Ω_b^- states. The yields of the baryons are obtained from the lifetime fits, and are listed in Table 1, along with our measurements of the relative production rates for the Ξ_b^- and Ω_b^-.

Table 1: Properties obtained for b-hadrons.

Resonance	Candidates	Mass (MeV/c^2)	$c\tau$ (μm)	$\frac{\sigma\mathscr{B}}{\sigma(\Lambda_b^0)\mathscr{B}(\Lambda_b^0\to J/\psi\,\Lambda)}$
$B^0(J/\psi\,K^*(892)^0)$	17520 ± 305	5279.2 ± 0.2	453 ± 6	-
$B^0(J/\psi\,K_s^0)$	9424 ± 167	5280.2 ± 0.2	448 ± 7	-
Λ_b^0	1934 ± 93	5620.3 ± 0.5	472 ± 17	-
Ξ_b^-	66^{+14}_{-9}	$5790.9\pm2.6\pm0.8$	$468^{+82}_{-74}\pm0.06$	$0.167^{+0.037}_{-0.025}\pm0.012$
Ω_b^-	16^{+6}_{-4}	$6054.4\pm6.8\pm0.9$	$340^{+160}_{-120}\pm0.04$	$0.045^{+0.017}_{-0.012}\pm0.004$

5. Conclusions

In conclusion, we have used data collected with the CDF II detector at the Tevatron to observe a signal of 16^{+6}_{-4} Ω_b^- candidates, with a significance equivalent to 5.5σ when combining both mass and lifetime information. The mass, lifetime and relative production rates of the Ω_b^- and Ξ_b^- are measured with the best level of precision that has been obtained.

References

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[2] C. Amsler *et al.* (Particle Data Group), Phys. Lett. **B 667**, 1 (2008).