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Production and Decay of Ξ_c^0 at *BABAR*

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Using 116.1 fb^{-1} of data collected by the *BABAR* detector, we present an analysis of Ξ_c^0 production in B decays and from the $c\bar{c}$ continuum, with the Ξ_c^0 decaying into $\Omega^- K^+$ and $\Xi^- \pi^+$ final states. We measure the ratio of branching fractions $\mathcal{B}(\Xi_c^0 \to \Omega^- K^+)/\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$ to be $0.294 \pm 0.018 \pm 0.016$, where the first uncertainty is statistical and the second is systematic. The Ξ_c^0 momentum spectrum is measured on and 40 MeV below the $\Upsilon(4S)$ resonance. From these spectra the branching fraction product $\mathcal{B}(B \to \Xi_c^0 X) \times \mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$ is measured to be $(2.11 \pm 0.19 \pm 0.25) \times 10^{-4}$, and the cross-section product $\sigma(e^+e^- \to \Xi_c^0 X) \times \mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$ from the continuum is measured to be $(388 \pm 39 \pm 41)$ fb at a center-of-mass energy of 10.58 GeV.

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In this Letter we present a study of the $\Xi_c^0(csd)$ [1] charmed baryon through two decay modes: $\Xi_c^0 \to \Omega^- K^+$ and $\Xi_c^0 \to \Xi^- \pi^+$ [2], the former of which is expected to proceed almost entirely via internal W exchange. We determine the ratio of branching fractions of these decay modes, which has been measured previously to be $0.50 \pm 0.21 \pm 0.05$ [3,4]. It was predicted to be 0.32 with a quark model calculation in which no spin information is exchanged between quarks other than through a single W boson [5].

We also study Ξ_c^0 production by measuring the spectrum of the Ξ_c^0 momentum in the e^+e^- center-of-mass frame (p^*). A number of theoretical predictions for Ξ_c production in B decays have been made [6–9]. There are several possible production mechanisms, principally $b \to c\bar{c}s$ weak decays, $b \to c\bar{u}d$ weak decays in which an $s\bar{s}$ pair is produced during fragmentation, and Cabibbo-suppressed $b \to c\bar{u}s$ weak decays. At this point there is insufficient experimental evidence to determine which of these is the dominant mechanism, and no clear theoretical consensus. Insight into the contributing processes can be gained by studying the shape of the p^* spectrum. Evidence for Ξ_c production in B decays was presented previously by the CLEO collaboration, with a statistical significance of $\sim 3\sigma$ in the $\Xi_c^0 \to \Xi^- \pi^+$ decay mode and $\sim 4\sigma$ in the $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$ decay mode [10].

The data for this analysis were collected with the *BABAR* detector at the SLAC PEP-II asymmetric energy e^+e^- collider; the detector is described in detail elsewhere [11]. A total integrated luminosity of 116.1 fb^{-1} is used, of which 105.4 fb^{-1} was collected at the $\Upsilon(4S)$ resonance [1] (corresponding to 116×10^6 $B\bar{B}$ pairs) and 10.7 fb^{-1} was collected at a center-of-mass energy of 10.54 GeV, which is below the $B\bar{B}$ production threshold. These are referred to as the on-resonance and off-resonance data samples, respectively.

The reconstruction of Ξ_c^0 candidates takes place as follows. A Λ candidate is reconstructed by identifying a proton and combining it with an oppositely charged track interpreted as a π^-, fitting the tracks to a common vertex. The Λ candidate is then combined with a negatively charged track interpreted as a π^- (K^-) to form a Ξ^- (Ω^-) candidate. For each intermediate hyperon, the invariant mass is required to be within 3σ of the central value, where σ is the fitted mass resolution. The invariant mass is then constrained to the nominal value [1]. Each resulting Ξ^- (Ω^-) candidate passing the selection criteria is then combined with a positively charged track interpreted as a π^+ (K^+) to form a Ξ_c^0 candidate. For the $\Omega^- K^+$ final state, the two $K^\pm$ tracks must be identified as kaons. Particle identification is performed with dE/dx and Cherenkov angle measurements [11].

Additional selection criteria, described below, are used to improve the signal-to-background ratio. As a precaution against selection bias, these are optimized with subsamples of the data: 20 and 40 fb^{-1} for the $\Xi^- \pi^+$ and $\Omega^- K^+$ final states, respectively. A minimum decay distance of 2.5 mm (1.5 mm) between the event primary vertex and the Ξ^- (Ω^-) decay vertex in the plane perpendicular to the beam direction is required. The distance between the Ω^- and Λ decay vertices is required to be at least 3 mm. In addition, the relative positioning of vertices is required to be causally connected: we reject candidates in which the Ξ^- decays further from the primary vertex than its daughter Λ does, or where the displacement vector from the Ω^- decay point to the Λ decay point is antiparallel to the Λ momentum vector [12]. The invariant mass distributions for the Ξ_c^0 candidates in the full data set satisfying these criteria are shown in Figs. 1(a) and 1(b) for $\Xi^- \pi^+$ and $\Omega^- K^+$ combinations, with signal yields of approximately 8100 and 1000 events, respectively.

Simulated events with the Ξ_c^0 decaying into the two desired final states are generated for the processes $e^+e^- \to c\bar{c} \to \Xi_c^0 X$ and $e^+e^- \to \Upsilon(4S) \to B\bar{B} \to \Xi_c^0 X$, where X represents the rest of the event. The PYTHIA simulation package [13], tuned to the global *BABAR* data, is used for the $c\bar{c}$ fragmentation and for B decays to Ξ_c^0, and GEANT4 [14] is used to simulate the detector response. For $c\bar{c}$ production, samples of 90 000 events for the $\Xi^- \pi^+$ final state and 60 000 for the $\Omega^- K^+$ final state are generated. For $B\bar{B}$ production, samples of 255 000 and 120 000 events are used, respectively.

Additional generic Monte Carlo events are used to investigate possible background contributions. The sample sizes are equivalent to 245, 64, and 33 fb^{-1} for $e^+e^- \to B\bar{B}$, $c\bar{c}$, and $q\bar{q}$, respectively, where $q = u, d, s$. Excluding signal contributions, the mass distribution varies smoothly throughout the region near the Ξ_c^0 mass.

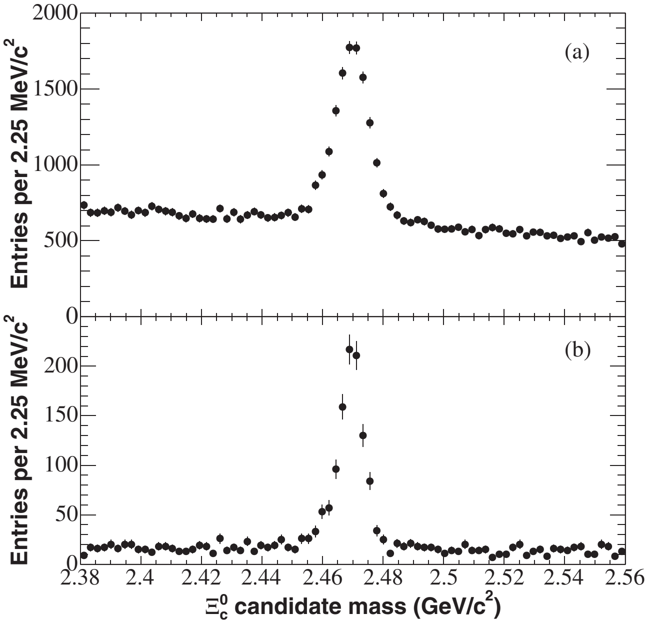

FIG. 1. Invariant mass distributions for Ξ_c^0 candidates in 116.1 fb^{-1} of data, for (a) $\Xi^-\pi^+$, and (b) Ω^-K^+.

To measure the ratio of branching fractions, a further requirement that $p^* > 1.8$ GeV$/c$ is imposed on the Ξ_c^0 candidates in order to suppress combinatoric background and improve the signal purity. Additionally, the candidates are required to be within the region of high Ξ_c^0 reconstruction efficiency $-0.8 \leq \cos\theta^* \leq 0.6$, where θ^* is the polar angle of the Ξ_c^0 candidate with respect to the collision axis in the center-of-mass frame. After these criteria, the signal yields for the $\Xi^-\pi^+$ and Ω^-K^+ modes are approximately 3650 and 650, respectively. The efficiency is calculated from signal Monte Carlo events as a function of p^* and $\cos\theta^*$ for each of the decay modes. For each mode, a 15-parameter fit gives a smooth parameterization of the efficiency with small statistical uncertainty. The efficiency is then corrected by weighting each candidate by the inverse of its efficiency, and the efficiency-corrected mass spectrum is fitted with a double Gaussian with a common mean for signal plus a linear background function. Including efficiency loss due to the Ω^- and Λ branching fractions, we obtain $25\,889 \pm 516$ weighted events in the $\Xi^-\pi^+$ mode and 7615 ± 443 weighted events in the Ω^-K^+ mode. The χ^2 fit probabilities are 65% and 5%, respectively. In each case, the wider Gaussian contributes approximately one quarter of the yield.

We evaluate several sources of systematic uncertainty in the ratio of branching fractions: the fits to the mass spectra (3.4%), the efficiency parameterization (3.1%), particle identification (2.0%), finite Monte Carlo statistics (1.4%), multiple candidates in the same event (1.0%), charge asymmetries in detection efficiency (1.0%), the $\cos\theta^*$ distribution (1.0%), and the Ω^- branching fraction (1.0%). No baryon polarization is considered and any systematic uncertainty due to this is neglected. Adding all of the uncertainties in quadrature, we obtain

$$\frac{\mathcal{B}(\Xi_c^0 \to \Omega^- K^+)}{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)} = 0.294 \pm 0.018 \pm 0.016.$$

After obtaining the ratio of branching fractions, we next measure the p^* spectrum of the Ξ_c^0 baryons in order to study the production mechanisms in both $c\bar{c}$ and $B\bar{B}$ events. The same selection criteria and data samples described above are used, except that no requirement on p^* or $\cos\theta^*$ is made. Instead, the Ξ_c^0 candidates are divided into intervals of p^*. The yield is then measured in each interval with two different methods: first with a fitting method, where the mass spectrum is fitted with a single Gaussian for signal plus a linear background function and the integral of the Gaussian is taken as the yield; second with a counting method, where the background is estimated from mass sidebands and the signal yield is then taken as the statistical excess above this background in a mass window around the peak. The use of two different methods serves as a cross-check.

The efficiency in each p^* interval is estimated with signal Monte Carlo events from that p^* range. For both methods, the simulated events are reconstructed and the yield is measured, then divided by the number of events generated to obtain the efficiency. Because of the different angular distributions, the efficiencies for Ξ_c^0 produced from $c\bar{c}$ ($\varepsilon_{c\bar{c}}$) and from $B\bar{B}$ ($\varepsilon_{B\bar{B}}$) differ slightly. In the region $1.2 < p^* < 2.0$ GeV$/c$ where both production mechanisms are significant and the difference is approximately 8% (relative), the efficiency is taken to be $(\varepsilon_{c\bar{c}} + \varepsilon_{B\bar{B}})/2$. The systematic uncertainty on the efficiency is then $|\varepsilon_{c\bar{c}} - \varepsilon_{B\bar{B}}|/\sqrt{12}$. The angular distributions produced in PYTHIA fragmentation are assumed to be correct when calculating the efficiency; the data are fully consistent with these distributions within available statistics. The efficiency-corrected yield in each p^* interval is then calculated, including loss of efficiency due to the Λ and Ω^- branching fractions. The spectra obtained with the two methods are in good agreement; we use the counting method for the quoted results since it is more stable for low statistics.

A number of systematic uncertainties are considered, the most important of which are the uncertainties associated with the track-finding and particle identification efficiencies (5.8% and 3.5%, respectively). Uncertainties from the simulated Ξ_c^0 mass resolution (1%), the mass resolutions of the intermediate hyperon states (0.5%), the p^* resolution [$\mathcal{O}(1\%)$], the effect of finite interval width [$\mathcal{O}(2\%)$], multiple candidates (0%), nonlinearity of the background [$\mathcal{O}(1\%)$], the signal measurement method used (2%), the finite Monte Carlo statistics available [$\mathcal{O}(3\%)$], and uncertainties in the Λ and Ω^- branching fractions (0.8%, 1.0%) are all considered individually; the notation $\mathcal{O}(x\%)$ indicates the typical value when the exact uncertainty varies among p^* intervals. The total systematic uncertainty for each p^* interval is obtained by adding the individual contributions in quadrature. In addition, a systematic correction of 1.0% is applied to account for a known data–Monte Carlo discrepancy in the track-finding efficiency, and small corrections are applied to each interval to account for the broadening effect of the p^* experimental resolution on the spectrum. The final p^* spectrum for the on-resonance data set, obtained with the counting method in the $\Xi^-\pi^+$ mode, is shown in Fig. 2(a). Table I shows the corresponding values.

A further check is performed by comparing the two decay modes. The Ω^-K^+ yields are scaled by a factor of (1/0.294), the ratio of branching fractions previously presented in this Letter. Because the Ω^-K^+ signal has fewer events, wider p^* intervals are used. The spectra of the two modes show good agreement in both shape and normalization and have a χ^2 probability of 80% for consistency. This serves as a cross-check both of the p^* spectrum measurement and of the ratio of branching fractions.

The double-peak structure seen in the p^* spectrum is due to two production mechanisms: the peak at lower p^* is due to Ξ_c^0 production in B meson decays and the peak at higher p^* is due to Ξ_c^0 production from the $c\bar{c}$ continuum. This is evident from Fig. 2(b), where the p^* spectra for the on-resonance and off-resonance data are shown separately (with the off-resonance spectrum scaled to the on-resonance integrated luminosity and corrected for the change in $c\bar{c}$ cross section). Table II shows the corresponding values. The $c\bar{c}$ peak is present in both samples, but the $B\bar{B}$ peak is only present in the on-resonance sample. Assuming baryon number conservation, the kinematic limit for Ξ_c^0 produced in the decays of B mesons at *BABAR* is $p^* = 2.135$ GeV/c. We compare the on-resonance and scaled off-resonance samples for $p^* \leq 2.15$ GeV/c to obtain the yield of Ξ_c^0 produced in B decays. This is scaled by the number of B mesons in the data sample (introducing a further 1.1% systematic uncertainty) to obtain

$$\mathcal{B}(B \to \Xi_c^0 X) \times \mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) = (2.11 \pm 0.19 \pm 0.25) \times 10^{-4}. \quad (1)$$

The yield of Ξ_c^0 produced in $c\bar{c}$ events at an energy of 10.58 GeV is calculated from the scaled off-resonance data set (for $p^* \leq 2.15$ GeV/c) and the on-resonance data set (for $p^* > 2.15$ GeV/c). The yield is then divided by the integrated luminosity (introducing a further 1.5% systematic uncertainty) to obtain the cross section from the con-

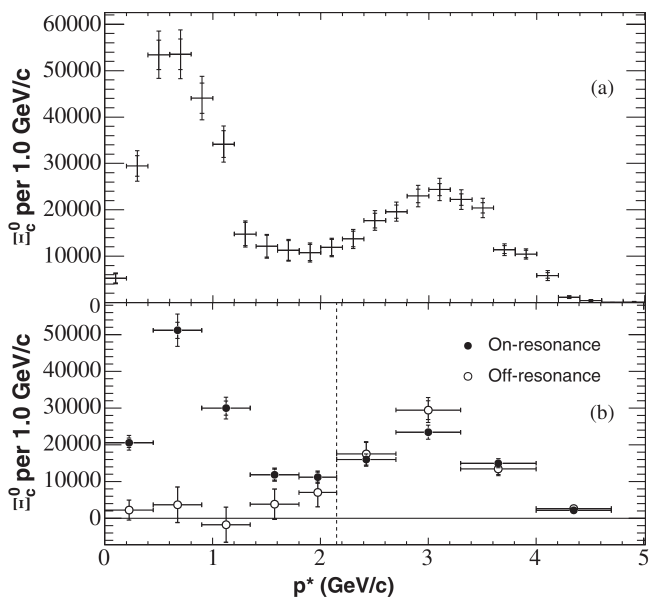

FIG. 2. The p^* spectrum measurements. In (a) the p^* spectrum of Ξ_c^0 decaying via $\Xi^-\pi^+$ is shown for the on-resonance data sample. In (b) the on-resonance and off-resonance data samples are shown together, with the off-resonance normalization scaled to account for the difference in integrated luminosity and cross section. In each plot, the inner error bars give the statistical uncertainty and the outer error bars give the sum in quadrature of the statistical and systematic uncertainties. The vertical line at 2.15 GeV/c in (b) shows the kinematic cutoff for Ξ_c^0 produced in B decays at *BABAR*. Note that the vertical axes show events per unit p^*, not events in each p^* bin as given in Table I.

TABLE I. Efficiency-corrected yield and cross-section product including B production $\sigma(e^+e^- \to \Xi_c^0 X) \times \mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)$, for the on-resonance data.

p^* range (GeV/c)	Corrected yield	Cross-section product (fb)
0.0–0.2	1046 ± 201 ± 128	10 ± 2 ± 1
0.2–0.4	5889 ± 446 ± 483	56 ± 4 ± 5
0.4–0.6	10681 ± 631 ± 801	101 ± 6 ± 8
0.6–0.8	10709 ± 660 ± 817	102 ± 6 ± 8
0.8–1.0	8811 ± 647 ± 679	84 ± 6 ± 7
1.0–1.2	6834 ± 573 ± 530	65 ± 5 ± 5
1.2–1.4	2954 ± 501 ± 252	28 ± 5 ± 2
1.4–1.6	2429 ± 470 ± 212	23 ± 4 ± 2
1.6–1.8	2252 ± 424 ± 202	21 ± 4 ± 2
1.8–2.0	2159 ± 350 ± 217	20 ± 3 ± 2
2.0–2.2	2375 ± 347 ± 205	23 ± 3 ± 2
2.2–2.4	2743 ± 340 ± 227	26 ± 3 ± 2
2.4–2.6	3537 ± 315 ± 285	34 ± 3 ± 3
2.6–2.8	3920 ± 282 ± 306	37 ± 3 ± 3
2.8–3.0	4595 ± 294 ± 359	44 ± 3 ± 3
3.0–3.2	4873 ± 263 ± 401	46 ± 2 ± 4
3.2–3.4	4442 ± 244 ± 348	42 ± 2 ± 3
3.4–3.6	4084 ± 223 ± 355	39 ± 2 ± 3
3.6–3.8	2282 ± 171 ± 189	22 ± 2 ± 2
3.8–4.0	2095 ± 155 ± 166	20 ± 1 ± 2
4.0–4.2	1168 ± 123 ± 177	11 ± 1 ± 2
4.2–4.4	233 ± 53 ± 32	2.2 ± 0.5 ± 0.3
4.4–4.6	88 ± 37 ± 21	0.8 ± 0.3 ± 0.2
4.6–4.8	5 ± 13 ± 7	0.0 ± 0.1 ± 0.1
4.8–5.0	24 ± 17 ± 16	0.2 ± 0.2 ± 0.1

TABLE II. Cross-section product including B production $\sigma(e^+e^- \to \Xi_c^0 X) \times \mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$, for the on- and off-resonance data. The off-resonance cross sections are scaled to a center-of-mass energy of 10.58 GeV.

p^* range (GeV/c)	Cross-section product (fb)	
	On resonance	Off resonance
0.00–0.45	$88 \pm 5 \pm 7$	$10 \pm 12 \pm 1$
0.45–0.90	$218 \pm 9 \pm 17$	$16 \pm 21 \pm 2$
0.90–1.35	$128 \pm 8 \pm 10$	$-7 \pm 20 \pm 2$
1.35–1.80	$51 \pm 6 \pm 4$	$16 \pm 18 \pm 2$
1.80–2.15	$37 \pm 4 \pm 3$	$23 \pm 13 \pm 2$
2.15–2.70	$83 \pm 5 \pm 6$	$91 \pm 16 \pm 7$
2.70–3.30	$133 \pm 4 \pm 10$	$168 \pm 15 \pm 13$
3.30–4.00	$99 \pm 3 \pm 8$	$89 \pm 10 \pm 7$
4.00–4.70	$14 \pm 1 \pm 1$	$17 \pm 4 \pm 2$

tinuum

$$\sigma(e^+e^- \to \Xi_c^0 X) \times \mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) = (388 \pm 39 \pm 41)\ \text{fb}, \quad (2)$$

where both Ξ_c^0 and $\bar{\Xi}_c^0$ are included in the cross section. The effect of initial state radiation is not isolated.

In summary, we have studied the Ξ_c^0 charmed baryon at *BABAR* through its decays to the $\Omega^- K^+$ and $\Xi^- \pi^+$ final states using 116.1 fb^{-1} of data. The ratio of branching fractions of these decay modes was measured to be $0.294 \pm 0.018 \pm 0.016$. This represents a substantial improvement on the previous measurement [3] and is consistent with a quark model prediction [5]. We have also measured the p^* spectrum for Ξ_c^0 produced at the $\Upsilon(4S)$ resonance. The high rate of Ξ_c^0 production at low p^* in B decays (below 1.2 GeV/c) is particularly intriguing, implying that the invariant mass of the recoiling antibaryon system is typically above 2.0 GeV/c^2. This can be explained naturally by a substantial rate of charmed baryon pair production through the $b \to c\bar{c}s$ weak decay process [6–9] which was observed indirectly in a previous *BABAR* analysis [15]. In this Letter we measured the branching fraction product $\mathcal{B}(B \to \Xi_c^0 X) \times \mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$ to be $(2.11 \pm 0.19 \pm 0.25) \times 10^{-4}$; the precision is significantly improved over the previous measurement [10]. We have also measured the cross-section product $\sigma(e^+e^- \to \Xi_c^0 X) \times \mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$ from the continuum to be $(388 \pm 39 \pm 41)$ fb.

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