Measurement of Ξ_c production in e^+e^- annihilation at 10.5 GeV center-of-mass energy

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Using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY, we have observed production of the charmed-strange baryon Ξ_c^+ and its neutral isospin partner, the Ξ_c^0. The Ξ_c^+ was reconstructed in the final state $\Xi^-\pi^+\pi^+$, while the Ξ_c^0 was seen in decay to $\Xi^-\pi^+$ and $\Xi^-\pi^+\pi^+\pi^-$. The average Ξ_c fragmentation spectrum has been determined, as well as the production cross section times branching ratio for each decay mode. The charged and neutral masses were measured to be $2465.1\pm3.6\pm1.9$ MeV/c^2 and $2472.1\pm2.7\pm1.6$ MeV/c^2 respectively, corresponding to a mass-splitting, $M(\Xi_c^+)-M(\Xi_c^0)$, of $-7.0\pm4.5\pm2.2$ MeV/c^2.

Evidence for the charmed-strange baryon Ξ_c^+ was first claimed by the WA62 experiment at CERN, who reported a signal for the decay $\Xi_c^+\to\Lambda K^-\pi^+\pi^+$ [#1] [1]. Experiment E400 [2] at FNAL later announced confirmation of this channel. However, the consistency of the two results is debatable, since E400 actually observed two peaks, one from the decay to $\Lambda K^-\pi^+\pi^+$, and the second attributed to the mode $\Xi_c^+\to\Sigma^0K^-\pi^+\pi^+$ where the photon from the Σ^0 decay goes undetected. In contrast, the WA62 study reported a single peak. Recently, both CLEO [3] and ACCMOR [4] have observed the Ξ_c^+, as well as its neutral isospin partner, the Ξ_c^0, and have measured the mass-splitting between the two states.

A number of models have been developed which provide a framework for calculation of the masses of charmed baryons [5,6]. A comparison of the predictions with experimental data provides a test of these various theoretical approaches. The predictions for the Ξ_c masses vary from 2420 MeV/c^2 up to 2579 MeV/c^2. Calculations of the isospin mass-splitting have also been carried out [6,7], leading to values for $M(\Xi_c^+)-M(\Xi_c^0)$ between -4.5 MeV/c^2 and 3.6 MeV/c^2.

Here we present a study of neutral and charged Ξ_c production using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. The analysis was based on a data sample of 355 pb^{-1} collected on the Υ(4S) resonance and in the nearby continuum. The ARGUS detector is a 4π spectrometer described in detail elsewhere [8]. Charged tracks were required to have momenta transverse to the beam direction greater than 60 MeV/c, with a polar angle, θ, such that $|\cos\theta|<0.92$. Charged particles were identified on the basis of specific ionization and time-of-flight measurements. This information was combined into an overall likelihood ratio for each of the allowed particle hypotheses (e, μ, π, K, and p). All hypotheses for which the likelihood ratio [8] exceeded 1% were accepted.

The search for charmed-strange baryons was made in the decay modes $\Xi_c^0\to\Xi^-\pi^+$, $\Xi_c^0\to\Xi^-\pi^+\pi^+\pi^-$, and $\Xi_c^+\to\Xi^-\pi^+\pi^+$, where the Ξ^- baryon was reconstructed in its decay $\Xi^-\to\Lambda\pi^-$. Λ candidates were selected from $p\pi^-$ pairs forming a secondary decay vertex. A mass-constraint fit was applied to each combination having an invariant mass within ±10 MeV/c^2 of the nominal Λ mass [9] and a χ^2 of less than 25 for the Λ mass hypothesis. Because of the long lifetime of the Ξ^-, the π^- meson from Ξ^- decays was not required to point back to the main interaction

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[#1] References in this paper to a specific charged state are to be interpreted as implying the charge-conjugate state also.

vertex. The resulting $\Lambda\pi^-$ mass spectrum (fig. 1) shows a Ξ^- signal of 803 ± 48 events. The additional structures in the distribution are due to a reflection of the Λ, near 1280 MeV/c^2, and to the $\Sigma(1385)^-$. For further analysis a mass-constraint fit was applied to those $\Lambda\pi^-$ combinations having an invariant mass within ±12 MeV/c^2 (or ±3 sigma) of the nominal Ξ^- mass [9]. Finally, since the charm fragmentation process leads to a rather hard momentum distribution for particles containing a primary charmed quark, the $\Xi^-\pi^+$, $\Xi^-\pi^+\pi^+\pi^-$ and $\Xi^-\pi^+\pi^+$ combinations were required to have a scaled momentum $x_p>0.5$, where $x_p=p/p_{\max}$ and $p_{\max}=\sqrt{E^2_{\text{beam}}-M^2}$. Here p and M are the momentum and mass of the $\Xi^-\pi^+$, $\Xi^-\pi^+\pi^+\pi^-$ or $\Xi^-\pi^+\pi^+$ combination.

The invariant mass spectra of all accepted $\Xi^-\pi^+$ and $\Xi^-\pi^+\pi^+\pi^-$ combinations are shown figs. 2 and 3. In both plots, a signal at a mass of about 2475 MeV/c^2 is observed. The spectra were fitted with the sum of a gaussian to describe the signal, and a third-order polynomial to parameterize the combinatorial background. The widths of the gaussians were fixed to 15.5 MeV/c^2 and 10.0 MeV/c^2 for figs. 2 and 3 respectively, as determined from Monte Carlo studies. The fits found 18.3 ± 5.6 events at a mass of 2475.7 ± 6.2 MeV/c^2 for fig. 2, and 36.2 ± 9.1 events at a mass of 2471.2 ± 3.0 MeV/c^2 for fig. 3. The two mass determinations are in good agreement.

The invariant mass distribution for the accepted

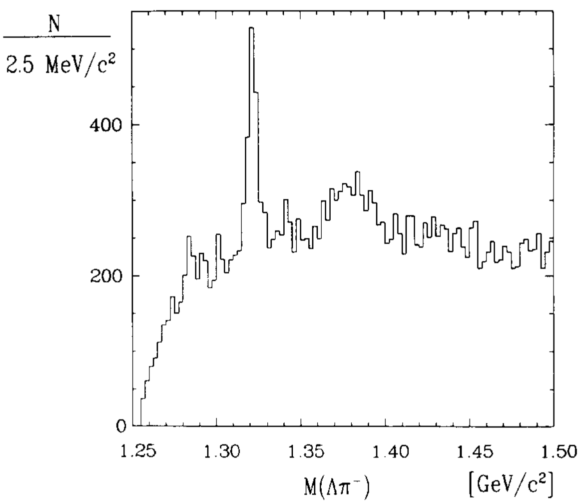

Fig. 1. $\Lambda\pi^-$ mass spectrum.

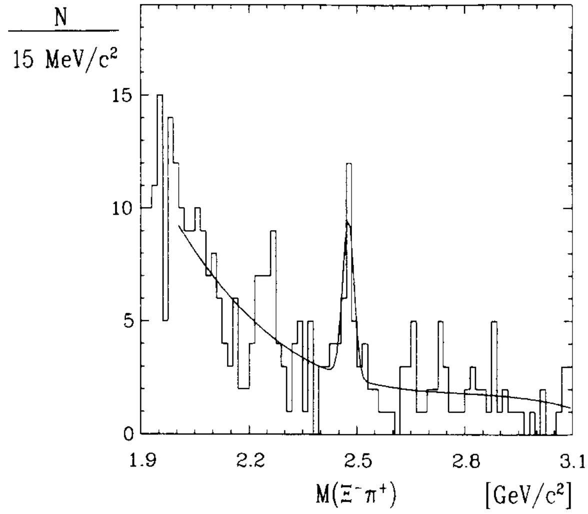

Fig. 2. $\Xi^-\pi^+$ mass spectrum for $x_p>0.5$. The curve corresponds to the fit described in the text.

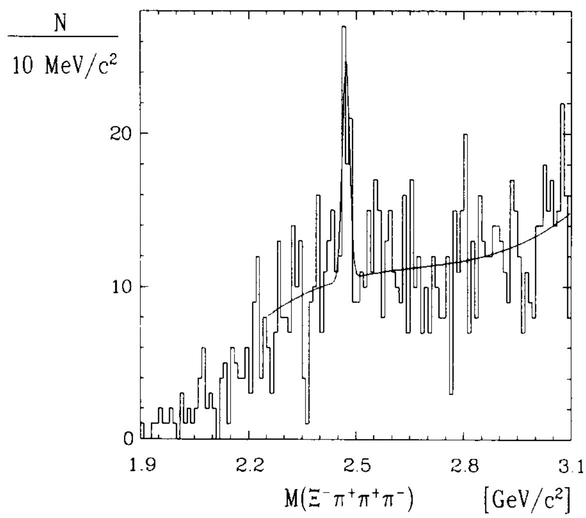

Fig. 3. $\Xi^-\pi^+\pi^+\pi^-$ mass spectrum for $x_p>0.5$. The curve corresponds to the fit described in the text.

$\Xi^-\pi^+\pi^+$ combinations is shown in fig. 4. A signal is evident near a mass of 2465 MeV/c^2. On the basis of a fit using the sum of a gaussian with width fixed to 12 MeV/c^2, plus a third-order polynomial, the signal was found to consist of 30.2 ± 7.9 events at a mass of 2465.1 ± 3.6 MeV/c^2.

Close examination of various reflection sources has

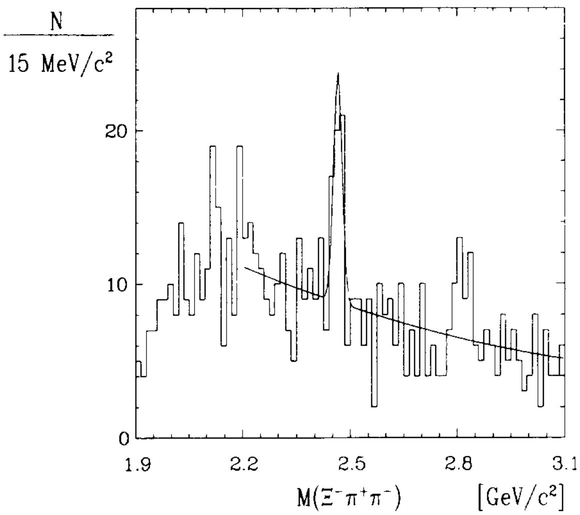

Fig. 4. $\Xi^-\pi^+\pi^+$ mass spectrum for $x_p > 0.5$. The curve corresponds to the fit described in the text.

shown that a signal cannot be artificially produced. For example, it is possible that a slow π^- combined with the final states $\Lambda_c^+ \to \Lambda\pi^+$ or $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$ could lead to a contribution in the signal range of $\Xi_c^0 \to \Xi^-\pi^+$ or $\Xi_c^0 \to \Xi^-\pi^+\pi^+\pi^-$ respectively. However, a Monte Carlo study showed these effects to be negligible. We also searched for possible background from charmed meson decays with a K_s^0 in the final state, which could be misidentified as a Λ. Again it was determined that charmed mesons do not contribute to our spectra. Finally, wrong-charge combinations and Ξ^- sideband spectra were studied for all decay modes, with no enhancements seen in the signal range.

The uncertainty in the ARGUS mass scale was estimated by comparing the observed masses for the decays $\Xi^- \to \Lambda\pi^-$, $D^0 \to K^-\pi^+\pi^+\pi^-$, $D^+ \to K^-\pi^+\pi^+$, and $\Lambda_c^+ \to pK^-\pi^+$ with their accepted values [9]. Extrapolating the residual uncertainty to the region of the Ξ_c states leads to an estimated systematic error of ± 1.2 MeV/c^2 on the mass determination. The cuts, background shape and width were varied to estimate the uncertainty in the fitting procedure. These contribute a further error of ± 3 MeV/c^2 on the Ξ_c mass as measured for $\Xi_c^0 \to \Xi^-\pi^+$, ± 1 MeV/c^2 for $\Xi_c^0 \to \Xi^-\pi^+\pi^+\pi^-$ and ± 1.5 MeV/c^2 for $\Xi_c^+ \to \Xi^-\pi^+\pi^+$. The measured mass values for each decay mode, and the weighted mean for the Ξ_c^0, are summarized in table 1.

Based on these results, the isospin mass splitting, $M(\Xi_c^+) - M(\Xi_c^0)$, is found to be $-7.0 \pm 4.5 \pm 2.2$ MeV/c^2, where the systematic error includes the uncertainty due to the fitting procedure and the different energy losses for the various final-state configurations. This result agrees with the CLEO value of $-5.0 \pm 4.0 \pm 1.0$ MeV/c^2 [3] and with the ACCMOR value of $-6.8 \pm 3.3 \pm 0.5$ MeV/c^2 [4].

A Monte Carlo simulation was performed to determine the detector acceptance. For all decay modes, the acceptance was found, for $x_p > 0.45$, to be practically independent of x_p. The efficiencies for $\Xi_c \to \Xi^-\pi^+$, $\Xi_c^0 \to \Xi^-\pi^+\pi^+\pi^-$ and $\Xi^+ \to \Xi^-\pi^+\pi^+$ for $x_p > 0.5$, are (10.8 ± 0.3)%, (6.4 ± 0.4)% and (9.0 ± 0.3)% respectively including the branching ratio for $\Lambda \to p\pi^-$. The production cross section times branching ratio results are summarized in table 2. The systematic errors include contributions from the uncertainty of the luminosity determination, the background estimation, the predicted widths, and the efficiency calculation. The ratio $BR(\Xi_c^0 \to \Xi^-\pi^+)/BR(\Xi_c^0 \to \Xi^-\pi^+\pi^+\pi^-)$, for which most of the systematic errors cancel, is $0.30 \pm 0.12 \pm 0.05$.

Table 1
Summary of mass measurements for Ξ_c^0 and Ξ_c^+.

Decay mode	Measured mass (MeV/c^2)
$\Xi_c^0 \to \Xi^-\pi^+$	$2475.7 \pm 6.2 \pm 3.2$
$\Xi_c^0 \to \Xi^-\pi^+\pi^+\pi^-$	$2471.2 \pm 3.0 \pm 1.6$
Ξ_c^0, weighted mean	$2472.1 \pm 2.7 \pm 1.6$
$\Xi_c^+ \to \Xi^-\pi^+\pi^+$	$2465.1 \pm 3.6 \pm 1.9$
$M(\Xi_c^+) - M(\Xi_c^0)$	$-7.0 \pm 4.5 \pm 2.2$

Table 2
Cross sections times branching ratios for Ξ_c^0 and Ξ_c^+ production at $E_{cms} = 10.5$ GeV.

Decay mode	$\sigma \cdot$BR	
	$x_p > 0.5$ (pb)	all x_p (pb)
$\Xi_c^0 \to \Xi^-\pi^+$	$0.48 \pm 0.15 \pm 0.08$	$0.77 \pm 0.24 \pm 0.16$
$\Xi_c^0 \to \Xi^-\pi^+\pi^+\pi^-$	$1.59 \pm 0.40 \pm 0.17$	$2.55 \pm 0.64 \pm 0.39$
$\Xi_c^+ \to \Xi^-\pi^+\pi^+$	$0.95 \pm 0.25 \pm 0.10$	$1.50 \pm 0.39 \pm 0.23$

In order to extract the fragmentation function for the charmed-strange baryons, it was necessary to combine the decay modes $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ and $\Xi_c^0 \to \Xi^-\pi^+\pi^+\pi^-$, due to limited statistics. Differences in the fragmentation functions of the charged and neutral Ξ_c baryons were thereby ignored. These might arise from the mass-splitting or from cascade decays of higher states, for example. For this study the x_p cut was relaxed to $x_p > 0.45$, still high enough to exclude possible contributions from Ξ_c baryons produced in B meson decays. The numbers of events in four x_p intervals were measured by fitting the data for each decay mode using a gaussian with the mass constrained to the appropriate value from table 1, and the width fixed to the value determined from Monte Carlo, plus a polynomial background. Efficiency corrections were applied to each bin and the results for both decay modes were then combined. The resulting x_p spectrum is shown in fig. 5. The overlayed curve corresponds to the fit of the fragmentation function of Peterson et al. [10]

$$\frac{dN}{dx_p} \propto x_p^{-1}\left(1 - \frac{1}{x_p} - \frac{\epsilon}{1-x_p}\right)^{-2} .$$

The value found for the fragmentation parameter was

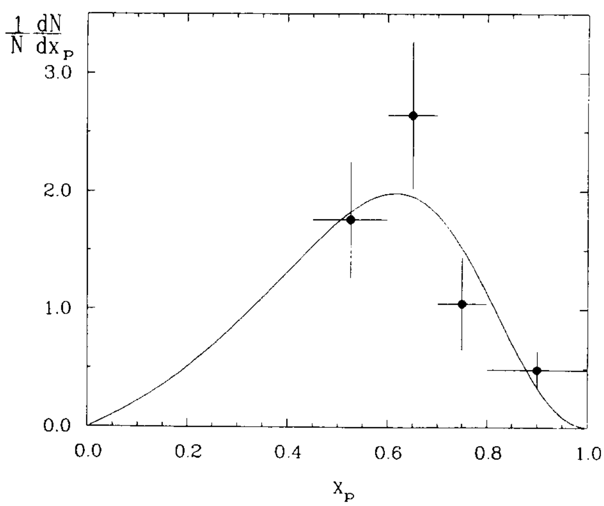

Fig. 5. Measured x_p spectrum for the combined signal of Ξ_c^0 and Ξ_c^+. The curve corresponds to the fit of the Peterson et al. fragmentation function to the spectrum.

$\epsilon = 0.24 \pm 0.08$ (with $\chi^2/\mathrm{NDF} = 3.6/2$). For comparison, the ARGUS values of ϵ for Λ_c^+ [11] and Σ_c [12] production are $(0.236^{+0.068}_{-0.048})$ and (0.29 ± 0.06), respectively.

The fitted fragmentation function was used to extrapolate the $\sigma \cdot \mathrm{BR}$ for $x_p > 0.5$ to the whole momentum range. The results are shown in table 2. The additional uncertainty introduced by the extrapolation has been included in the systematic error.

In summary, the production of the charmed-strange baryons Ξ_c^0 and Ξ_c^+ in e^+e^- annihilation at 10.5 GeV center-of-mass energy has been studied. In addition to confirmation of previously observed channels, we find first evidence for the decay $\Xi_c^0 \to \Xi^-\pi^+\pi^+\pi^-$. The masses of the Ξ_c^0 and Ξ_c^+ are measured to be $2472.1 \pm 2.7 \pm 1.6$ MeV/c^2 and $2465.1 \pm 3.6 \pm 1.9$ MeV/c^2 respectively, leading to an isospin mass-splitting of $M(\Xi_c^+) - M(\Xi_c^0) = -7.0 \pm 4.5 \pm 2.2$ MeV/c^2. A fit of the momentum spectrum of the Ξ_c with the fragmentation function of Peterson et al. yielded a value for the fragmentation parameter of $\epsilon = 0.24 \pm 0.08$.

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