Abstract

Using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY, we have found evidence for the production of the excited charmed baryon state $\Lambda_c(2593)^+$ in the channel $\Lambda_c^+\pi^+\pi^-$. Its mass was determined to be $(2594.6 \pm 0.9 \pm 0.4)$ MeV/c^2, and the natural width measured to be $\Gamma = (2.9^{+2.9}_{-2.1}{}^{+1.8}_{-1.4})$ MeV. The production cross section times the branching ratios of $\sigma(e^+e^- \rightarrow \Lambda_c(2593)^+X) \times Br(\Lambda_c(2593)^+ \rightarrow \Lambda_c^+\pi^+\pi^-) \times Br(\Lambda_c^+ \rightarrow pK^-\pi^+)$ was measured to be $(0.25^{+0.24}_{-0.13} \pm 0.13)$ pb. The fractions of $\Lambda_c(2593)^+$ decays proceeding through the $\Sigma_c^0\pi^+$ and $\Sigma_c^{++}\pi^-$ channels were determined to be $0.29 \pm 0.10 \pm 0.11$ and $0.37 \pm 0.12 \pm 0.13$, respectively.

1 Introduction

Most ground state charmed baryons are now well established [1], and the measurements confirm their mass predictions by theoretical models. As for the mass predictions for the excited charmed baryons, their experimental verification has been long overdue. New experimental observations would help to distinguish between different theoretical approaches [2]. The first observation of the excited charmed baryon [1] $\Lambda_c(2625)^+$ was made by the ARGUS Collaboration [3]. The E687[4] and CLEO[5] Collaborations subsequently confirmed this resonance. The CLEO Collaboration also reported the observation of another state decaying into $\Lambda_c^+\pi^+\pi^-$ at a mass of about 2593 MeV/c^2[5] which was referred to as the $\Lambda_c(2593)^+$, and the E687 Collaboration published the confirmation of this state[6]. Recently, the CLEO Collaboration presented the observation of two new charmed baryon states at masses of about 2518 MeV/c^2 and 2520 MeV/c^2 decaying into $\Lambda_c^+\pi^-$ and $\Lambda_c^+\pi^+$ [7], respectively. In the charmed strange baryon sector, the CLEO Collaboration has evidence for excited states decaying into $\Xi_c^+\pi^-$ [8] and $\Xi_c^0\pi^+$ [9]. In this paper we report on a study of the $\Lambda_c(2593)^+$ resonance in the decay channel $\Lambda_c^+\pi^+\pi^-$.

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[1] All references to a specific charged state also imply the charge conjugate state.

2 Selection criteria

The data used for this analysis was collected on the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(4S)$ resonances, and in the nearby continuum using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. The integrated luminosity of the data sample is equal to 476 pb^{-1}. The ARGUS detector, its trigger requirements and particle identification capabilities have been described in detail elsewhere [10]. Charged tracks from the main vertex were required to have a polar angle, θ, in the range $|\cos(\theta)| < 0.92$. Charged particle identification was based on a likelihood ratio calculated from measurements of specific ionization and time-of-flight for the allowed mass hypotheses (e, μ, π, K, and p) [10]. Each particle was used as a pion, kaon, or proton if the corresponding likelihood ratio exceeded 1%, 5%, or 15%, respectively. $\Lambda^0(K^0_s)$ candidates were defined as $p\pi^-(\pi^+\pi^-)$ pairs forming a secondary vertex and having an invariant mass within $\pm10(\pm30)$ MeV/c^2 of the nominal $\Lambda^0(K^0_s)$ mass. In addition it was required that $\cos(\alpha) > 0.995(0.9)$, where α is the angle between the $\Lambda^0(K^0_s)$ momentum and the vector pointing from the main vertex to the decay vertex. All Λ^0 and K^0_s candidates were kinematically constrained to their nominal masses [1]. For the Λ_c^+ reconstruction five decay modes were used - $pK^-\pi^+$, pK^0_s, $pK^0_s\pi^+\pi^-$, $\Lambda^0\pi^+$ and $\Lambda^0\pi^+\pi^-\pi^+$. All combinations having an invariant mass within ±25 MeV/c^2 (for the $pK^-\pi^+$, $\Lambda^0\pi^+\pi^-\pi^+$ and $pK^0_s\pi^+\pi^-$ modes), ±30 MeV/c^2 (for the pK^0_s mode) and ±40 MeV/c^2 (for the $\Lambda^0\pi^+$ mode) of the Λ_c^+ nominal mass [1] were considered as Λ_c^+ candidates and kinematically constraint to its mass.

Each selected Λ_c^+ candidate was combined with all $\pi^+\pi^-$ pairs in an event. The momentum spectra of charmed hadrons from the continuum in e^+e^- annihilation have proven to be hard compared to the combinatorial background, and therefore the requirement of a large scaled momentum $\mathrm{x_p}$, where $\mathrm{x_p} = p(\Lambda_c^+\pi^+\pi^-)/p_{max}$ and $p_{max} = \sqrt{E^2_{beam} - M^2(\Lambda_c^+\pi^+\pi^-)}$, is a good tool to improve the signal to background ratio. In this analysis the scaled momentum $\mathrm{x_p}$ of each $\Lambda_c^+\pi^+\pi^-$ combination was required to be greater than 0.7 if not stated otherwise.

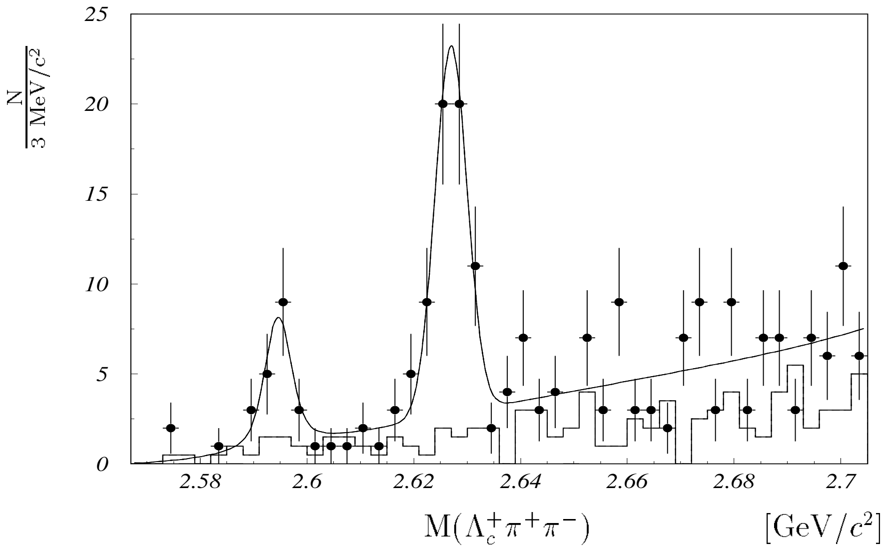

Figure 1: The $\Lambda_c^+\pi^+\pi^-$ invariant mass distribution. The solid histogram represents the same distribution but using the Λ_c^+ sidebands.

3 Data analysis

The invariant mass spectrum of all accepted $\Lambda_c^+\pi^+\pi^-$ combinations is shown in Figure 1. Two narrow peaks are seen at masses of about 2593 MeV/c^2 and 2625 MeV/c^2. The right peak corresponds to the previously observed $\Lambda_c(2625)^+$ resonance [1]. The solid histogram in Figure 1 represents the invariant mass spectrum for artificial $\Lambda_c^+\pi^+\pi^-$ combinations with the Λ_c^+ candidates taken from the sidebands. It has also been checked that the invariant mass spectra for wrong-charge combinations ($\Lambda_c^+\pi^-\pi^-$ and $\Lambda_c^+\pi^+\pi^+$) have a smooth behavior in the signal regions.

The lower-mass peak proved to be significantly wider than the expected detector resolution of 1.8 MeV/c^2 found from a Monte Carlo simulation. The spectrum presented in Figure 1 was fitted with the sum of a non-relativistic Breit-Wigner convoluted with a Gaussian resolution function parametrizing the lower-mass peak plus a pure Gaussian to describe the higher-mass signal [3, 5, 6]. The widths of the Gaussians were fixed to the expected values of 1.8 MeV/c^2 and 3.0 MeV/c^2, respectively. A background parametrization consisting of a second order polynomial, multiplied by a three body threshold factor completed the fit function. Using a Monte Carlo simulation procedure it was found that the mass resolutions and efficiencies do not substantially depend upon whether the baryons under study decay through a resonant $\Sigma_c\pi^\pm$ channel or not. The fit yields 18.8±5.9 and 51.3±8.2 events for the $\Lambda_c(2593)^+$ and $\Lambda_c(2625)^+$ states respectively. The masses $\mathrm{M}(\Lambda_c(2593)^+)$, $\mathrm{M}(\Lambda_c(2625)^+)$, and the mass difference of $\delta\mathrm{M} = \mathrm{M}(\Lambda_c(2625)^+) - \mathrm{M}(\Lambda_c(2593)^+)$ were measured to be $(2594.6 \pm 0.9 \pm 0.4)$ MeV/c^2, $(2627.0 \pm 0.5 \pm 0.5)$ MeV/^{2}, and $(32.4 \pm 1.0 \pm 0.7)$ MeV/c^2, respectively. The natural width for the $\Lambda_c(2593)^+$ state was obtained to be $\Gamma = (2.9^{+2.9+1.8}_{-2.1-1.4})$ MeV. We also measured the mass differences of $\mathrm{M}(\Lambda_c(2593)^+) - \mathrm{M}(\Lambda_c^+)$ and $\mathrm{M}(\Lambda_c(2625)^+) - \mathrm{M}(\Lambda_c^+)$ to be $(309.7 \pm 0.9 \pm 0.4)$ MeV/c^2 and $(342.1 \pm 0.5 \pm 0.5)$ MeV/c^2, respectively. The systematic errors come from varying the cuts, signal widths and background parametrization. An additional systematic error of 0.6 MeV/c^2 should be added to the mass measurements as the error in the world average Λ_c^+ mass [1]. The obtained $\Lambda_c(2593)^+$ parameters are in a good agreement with the results of the CLEO[5] and E687[6] Collaborations (see Table 1).

$\Lambda_c(2593)^+$ parameter, [MeV/c^2]	ARGUS	CLEO [5]	E687 [6]
$\mathrm{M}(\Lambda_c^{*+})$	$2594.6 \pm 0.9 \pm 0.4$		
$\mathrm{M}(\Lambda_c^{*+}) - \mathrm{M}(\Lambda_c^+)$	$309.7 \pm 0.9 \pm 0.4$	$307.5 \pm 0.4 \pm 1.0$	$309.2 \pm 0.7 \pm 0.3$
$\delta\mathrm{M}$	$32.4 \pm 1.0 \pm 0.7$	$34.7 \pm 0.5 \pm 1.2$	
$\Gamma(\Lambda_c^{*+})$	$2.9^{+2.9+1.8}_{-2.1-1.4}$	$3.9^{+1.4+2.0}_{-1.2-1.0}$	

Table 1: The extracted parameters of the $\Lambda^+(2593)$ baryon along with measurements of other groups.

To obtain the $\Lambda_c(2593)^+$ momentum distribution we fitted the invariant $\Lambda_c^+\pi^+\pi^-$ mass spectra in five $\mathrm{x_p}$ bins starting from $\mathrm{x_p} = 0.5$. The mass and width of the $\Lambda_c(2593)^+$ state were fixed to the values determined from the overall fit. Gaussian resolutions were fixed in each $\mathrm{x_p}$ bin to the appropriate values obtained from a Monte Carlo simulation. The resulting efficiency corrected $\Lambda_c(2593)^+$ momentum spectrum is shown in Figure 2. The efficiency in each $\mathrm{x_p}$ bin is the sum of the products of the reconstruction efficiency for the corresponding Λ_c^+ mode found from a Monte Carlo simulation and the ratio of $Br(\Lambda_c^+ \to X)/Br(\Lambda_c^+ \to pK^-\pi^+)$ for this mode [1]. The Peterson et. al. fragmentation function [14]

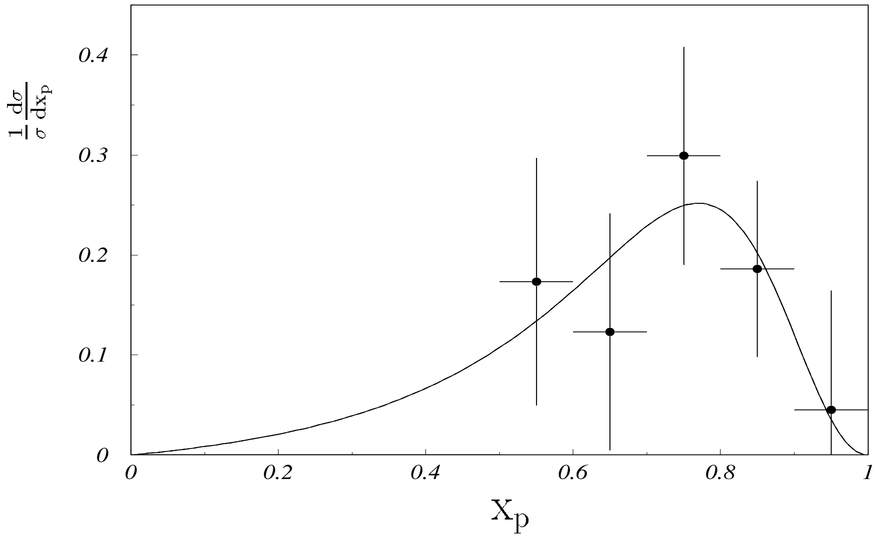

Figure 2: The x_p spectrum for $\Lambda_c(2593)^+$. The superimposed curve represents the fit with a Peterson et. al. fragmentation function.

$$\frac{d\sigma}{dx_p} \propto x_p{}^{-1}[1 - \frac{1}{x_p} - \frac{\epsilon}{1-x_p}]^{-2}$$

was used to fit this x_p spectrum and to obtain the total number of $\Lambda_c(2593)^+$ baryons produced in the entire momentum interval, and the fragmentation parameter ϵ. The fit results in $\epsilon = 0.069^{+0.065}_{-0.034} \pm 0.040$, and the production cross section times the branching ratios in e^+e^- annihilation at $\sqrt{s} = 10.4$ GeV:

$$\sigma(\Lambda_c(2593)^+) \times Br(\Lambda_c(2593)^+ \to \Lambda_c^+\pi^+\pi^-) \times Br(\Lambda_c^+ \to pK^-\pi^+)$$

$$= (0.25^{+0.24}_{-0.13} \pm 0.13) \text{ pb.}$$

The cross section in the momentum interval of $x_p > 0.7$ is equal to

$$\sigma(\Lambda_c(2593)^+|x_p > 0.7) \times Br(\Lambda_c(2593)^+ \to \Lambda_c^+\pi^+\pi^-) \times Br(\Lambda_c^+ \to pK^-\pi^+)$$

$$= (0.14 \pm 0.04 \pm 0.03) \text{ pb,}$$

which is free of the extrapolation uncertainty. The quoted systematic errors include the uncertainty on variation of the fit parameters in each x_p bin, the errors on the Monte Carlo reconstruction efficiency, and the errors on

$Br(\Lambda_c^+ \to X)/Br(\Lambda_c^+ \to pK^-\pi^+)$ [1]. Using the ARGUS measurement of $\sigma(\Lambda_c^+) \times Br(\Lambda_c^+ \to pK^-\pi^+) = (12.0 \pm 1.0 \pm 1.3)$ pb [13] the fraction of Λ_c^+ baryons produced from $\Lambda_c(2593)^+ \to \Lambda_c^+\pi^+\pi^-$ decays was found to be $(2.1^{+2.0}_{-1.1} \pm 1.1)$ %, in agreement with the analogous measurement of the CLEO Collaboration [5] of $(1.44 \pm 0.24 \pm 0.30)$ %.

An HQET[11] and some other models[12] predict that the $\Lambda_c(2593)^+$, being interpreted as a $\mathrm{J^P} = (\frac{1}{2})^-$ state, should have resonant $\Sigma_c\pi$ S-wave decay channels. Therefore the experimental resonant structure measurements in the decay $\Lambda_c(2593)^+ \to \Lambda_c^+\pi^+\pi^-$ can help to establish the identity of this state. For the $\Lambda_c(2593)^+$ state the CLEO [5] and E687 [6] Collaborations have found that substantial fractions of $\Lambda_c(2593)^+ \to \Lambda_c^+\pi^+\pi^-$ decays proceed through the $\Sigma_c\pi^\pm$ resonant channels. Here we present our investigation of the resonant structure in the $\Lambda_c(2593)^+ \to \Lambda_c^+\pi^+\pi^-$ decay. To get more statistics in this part of the analysis the $\mathrm{x_p}$ cut was relaxed to the value of 0.5.

In order to obtain the resonant contribution to the decay $\Lambda_c(2593)^+ \to \Lambda_c^+\pi^+\pi^-$ we performed a maximum likelihood fit to the $\Lambda_c^+\pi^+\pi^-$ invariant mass spectrum in bins of the $\Lambda_c^+\pi^+$ invariant mass. The $\Lambda_c(2593)^+$ parameters were fixed to the values found from the overall fit, and the mass resolution was fixed to the value found from a Monte Carlo simulation($\sigma = 1.9$ MeV/c^2). The spectrum obtained is presented in Figure 3, where two peaks on a small non-resonant background are clearly seen. The peak at a mass of 2453 MeV/c^2 is attributed to the Σ_c^{++} baryon, the peak at 2428 MeV/c^2 corresponds to a reflection of the Σ_c^0. This reflection arises because of the small phase space in the $\Lambda_c(2593)^+ \to \Sigma_c^0\pi^+(\Sigma_c^0 \to \Lambda_c^+\pi^-)$ decay. The $\Lambda_c^+\pi^+$ mass distribution was fitted using two Gaussians to describe the Σ_c^{++} signal and Σ_c^0 reflection plus a constant term times square-root threshold factor to describe the non-resonant contribution. The Gaussian widths and central values were fixed from a Monte Carlo simulation. The fit results in the following decay fractions for the $\Lambda_c(2593)^+$ state:

$$f_{\Sigma_c^0} = \frac{Br(\Lambda_c(2593)^+ \to \Sigma_c^0\pi^+)}{Br(\Lambda_c(2593)^+ \to \Lambda_c^+\pi^+\pi^-)} = 0.29 \pm 0.10 \pm 0.11,$$

$$f_{\Sigma_c^{++}} = \frac{Br(\Lambda_c(2593)^+ \to \Sigma_c^{++}\pi^-)}{Br(\Lambda_c(2593)^+ \to \Lambda_c^+\pi^+\pi^-)} = 0.37 \pm 0.12 \pm 0.13,$$

$$f_{nr} = \frac{Br(\Lambda_c(2593)^+ \to (\Lambda_c(2593)^+\pi^+\pi^-)_{nr})}{Br(\Lambda_c(2593)^+ \to \Lambda_c^+\pi^+\pi^-)} = 0.34^{+0.16}_{-0.13} \pm 0.07.$$

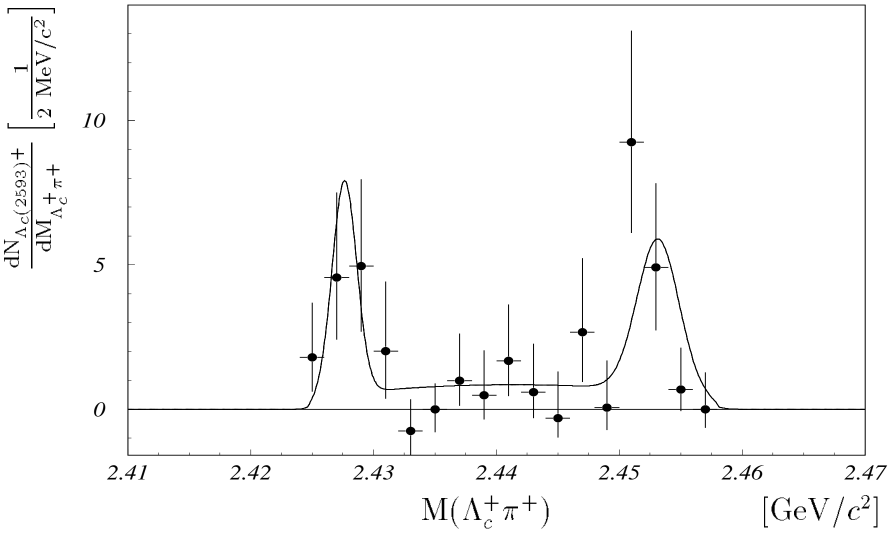

Figure 3: $\Lambda_c^+\pi^+$ invariant mass spectrum for $\Lambda_c(2593)^+$ decays. The overlayed curve is the fit described in the text.

Using the constraint $f_{\Sigma_c^0} + f_{\Sigma_c^{++}} + f_{nr} = 1$, the total fraction of $\Sigma_c\pi^\pm$ decays becomes $0.66^{+0.13}_{-0.16} \pm 0.07$. The systematic errors on the extracted fractions were evaluated by varying the fit parameters and the shape of the non-resonant function. Our measurement of the resonant decay fractions is in agreement with the results of the CLEO [5] and E687 [6] Collaborations(see Table 2).

$\Lambda_c(2593)^+$ decay fractions	ARGUS	CLEO [5]	E687 [6]
$f_{\Sigma_c^0}$	$0.29 \pm 0.10 \pm 0.11$	$0.42 \pm 0.09 \pm 0.09$	
$f_{\Sigma_c^{++}}$	$0.37 \pm 0.12 \pm 0.13$	$0.36 \pm 0.09 \pm 0.09$	
$f_{\Sigma_c^{0,++}}$	$0.66^{+0.13}_{-0.16} \pm 0.07$		> 0.51 @ 90% CL

Table 2: Summary of measurements for the $\Lambda^+(2593)$ decay fractions.

4 Conclusions

In summary, we confirmed the existence of the $\Lambda_c(2593)^+$ resonance and studied its production and decay in e^+e^- annihilation at 10.4 GeV center-of-mass energy.

The mass and the natural width of the $\Lambda_c(2593)^+$ state were measured to be $(2594.6 \pm 0.9 \pm 0.4 \pm 0.6)\mathrm{MeV/c}^2$ and $(2.9^{+2.9+1.8}_{-2.1-1.4})\mathrm{MeV}$, respectively. The mass differences of $\mathrm{M}(\Lambda_c(2593)^+) - \mathrm{M}(\Lambda_c^+)$ and $\mathrm{M}(\Lambda_c(2625)^+) - \mathrm{M}(\Lambda_c(2593)^+)$ were determined to be $(309.7 \pm 0.9 \pm 0.4)$ $\mathrm{MeV/c}^2$ and $(32.4 \pm 1.0 \pm 0.7)$ $\mathrm{MeV/c}^2$, respectively. The production cross section of $\sigma(\Lambda_c(2593)^+) \times Br(\Lambda_c(2593)^+ \rightarrow \Lambda_c^+\pi^+\pi^-) \times Br(\Lambda_c^+ \rightarrow pK^-\pi^+)$ was found to be $(0.25^{+0.24}_{-0.13} \pm 0.13)$ pb. The fractions of $\Lambda_c(2593)^+ \rightarrow \Lambda_c^+\pi^+\pi^-$ decays going through the $\Sigma_c^0\pi^+$ and $\Sigma_c^{++}\pi^0$ channels were determined to be $0.29 \pm 0.10 \pm 0.11$ and $0.37 \pm 0.12 \pm 0.13$, respectively. Our $\Lambda_c(2593)^+$ mass, natural width and resonant decay fraction measurements are in agreement with the CLEO [5] and E687 [6] Collaborations results.

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