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*The ARGUS Collaboration*

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**Abstract**

Using the ARGUS detector at the $e^+e^-$ storage ring DORIS II at DESY, we have observed a new charmed baryon state in the channel $\Lambda_c^+\pi^+\pi^-$ [1]. The mass of this state was measured to be $(2626.6 \pm 0.5 \pm 1.5)$ $MeV/c^2$. The product of the production cross section and branching ratio for this channel was determined to be $(11.5 \pm 2.5 \pm 3.0)$ $pb$, and the natural width estimated to be smaller than 3.2 $MeV/c^2$ at 90% CL.

Substantial progress has been made in charmed baryon physics during the last decade. Production of the $\Lambda_c^+$ in $e^+e^-$ annihilations was first observed by the MARK II Collaboration [1], followed by the neutral and doubly charged isospin partners $\Sigma_c^0$ and $\Sigma_c^{++}$ of the $\Sigma_c$ isotriplet observed by the ARGUS [2] collaboration, and the $\Xi_c^0$ and $\Xi_c^+$, seen by the CLEO [4] and ARGUS [3] collaborations. Last year the ARGUS collaboration reported the first evidence for the doubly strange charmed baryon $\Omega_c^0$ in $e^+e^-$ annihilations [5]. Thus, most ground state baryons containing one $c$-quark have been established. Here we present a search for an excited charmed baryon resonance $\Lambda_c^{*+}$ in the final state $\Lambda_c^+\pi^+\pi^-$. This choice of channel is justified because an excited $\Lambda_c^{*+}$ state would decay strongly into either $\Lambda_c^+\pi^+\pi^-$ or $\Sigma_c\pi$ but not into $\Lambda_c^+\pi$, which is forbidden by isospin conservation.

Since the pioneering work by De Rújula, Georgi and Glashow [6] a number of models have been developed to provide explicit predictions for the masses of excited charmed baryons [7-10]. An experimental verification is, however, up to now missing.

The data used in this analysis were collected using the ARGUS detector at the DORIS II storage ring at DESY, comprising an integrated luminosity of about 385 $pb^{-1}$ taken on the $\Upsilon(4S)$ resonance and in the nearby continuum. The ARGUS detector is a $4\pi$ magnetic spectrometer. Its trigger requirements and particle identification capabilities are described in detail elsewhere [11].

Only multihadron events were selected, these being defined as having at least three tracks with either a common vertex or a total energy deposition in the shower counters of more than 1.7 $GeV$. Charged tracks were required to originate from the main interaction region with a polar angle $\theta$ in the range $|cos(\theta)| < 0.92$, and momenta transverse to the beam direction greater then 60 $MeV/c$. The particle identification procedure was based on a combined likelihood ratio calculated from the measurements of specific ionization and time-of-flight for allowed mass hypotheses ($e, \mu, \pi$,K and p) [11]. A particle was treated as a pion, kaon or proton if the corresponding likelihood ratio exceeded 1%, 5% and 15%, respectively. Such cuts were chosen to obtain an optimal signal to background ratio for the $\Lambda_c^+$ as well as to suppress possible reflections from charmed mesons to a negligible level. $\Lambda^0(K_S^0)$ candidates were defined as a $p\pi^-(\pi^+\pi^-)$ pairs forming secondary vertices. A mass constraint fit was applied to each combination having an invariant mass within $\pm 10(\pm 30)$ $MeV/c^2$ of the nominal $\Lambda^0(K_S^0)$ mass [12], and those with a $\chi^2$ of less than 25 were used in the subsequent analysis. In addition the

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

angle $\alpha$ between the $\Lambda^0$ ($K^0_S$) flight direction and the vector pointing from the main vertex to the decay vertex was required to satisfy $\cos\alpha > 0.95(0.9)$.

The $\Lambda_c^+$ baryon was reconstructed in four decay modes - $pK^-\pi^+$, $pK^0_S$, $\Lambda^0\pi^+$, and $\Lambda^0\pi^+\pi^+\pi^-$. Each combination with an invariant mass lying within $\pm 25$ $MeV/c^2$ for $pK^-\pi^+$ and $\Lambda^0\pi^+\pi^+\pi^-$, $\pm 30$ $MeV/c^2$ for $pK^0_S$ and $\pm 40$ $MeV/c^2$ for $\Lambda^0\pi^+$ of the nominal $\Lambda_c^+$ mass [12] was subjected to a mass constraint fit to improve the momentum resolution.

Every $\Lambda_c^+$ candidate was then combined with all $\pi^+\pi^-$ pairs in an event. Charmed baryons are expected to be products of the initial charm quark fragmentation process, so they should possess rather large momenta, in contrast to the combinatorial background. Therefore the scaled momentum $x_p$ of all $\Lambda_c^+\pi^+\pi^-$ combinations was required to be greater than 0.5, where $x_p = p(\Lambda_c^+\pi^+\pi^-)/p_{max}$ and $p_{max} = \sqrt{E^2_{beam} - M^2(\Lambda_c^+\pi^+\pi^-)}$.

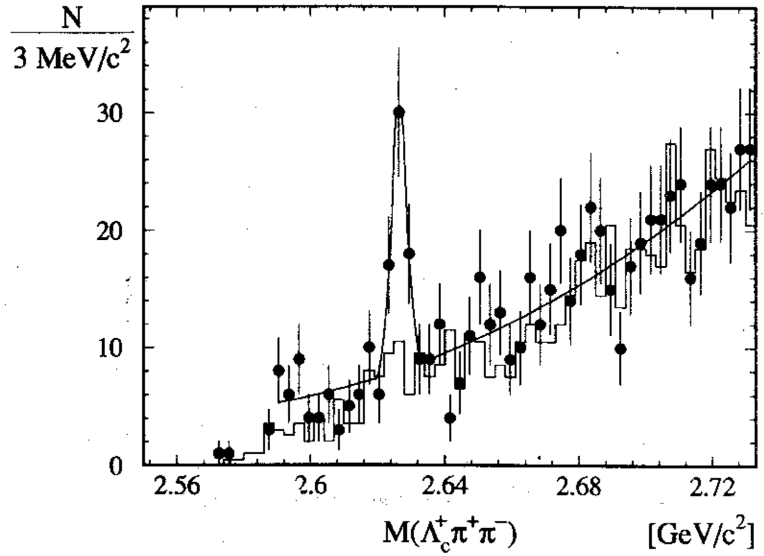


**Figure** 1: Invariant mass distribution for all accepted $\Lambda_c^+\pi^+\pi^-$ combinations. The solid histogram results from using the $\Lambda_c^+$ sidebands.

The resulting $\Lambda_c^+\pi^+\pi^-$ invariant mass spectrum is presented in Fig.1. A narrow peak at a mass of about 2627 $MeV/c^2$ is observed, while the distribution for artificial $\Lambda_c^+\pi^+\pi^-$ combinations built up from the $\Lambda_c^+$ sidebands shows a more or less smooth behaviour in this region. The spectrum was fit with a background function consisting of a second order polynomial and a Gaussian with free width and position to represent the signal. The fit resulted in $42.4 \pm 8.8$ events at a mass of $(2626.6 \pm 0.5)$ $MeV/c^2$ with a width of $\sigma = (2.2 \pm 0.5)$ $MeV/c^2$. This is consistent with the expected detector resolution of $(2.6 \pm 0.1)$ $MeV/c^2$ determined from a Monte



Carlo simulation. The mass and width of the signal proved to be stable against a variation of the $x_p$ cut. The results of the fits obtained with different $x_p$ cuts are summarized in Table 1.

| $x_p >$ | Mass ($MeV/c^2$) | $\sigma(MeV/c^2)$ | Entries |
|---|---|---|---|
| 0.4 | $2626.7 \pm 0.6$ | $2.3 \pm 0.5$ | $45.6 \pm 10.1$ |
| 0.5 | $2626.6 \pm 0.5$ | $2.2 \pm 0.5$ | $42.4 \pm 8.8$ |
| 0.6 | $2626.7 \pm 0.5$ | $2.1 \pm 0.4$ | $34.9 \pm 7.5$ |

**Table** 1: Summary of results from fitting the $\Lambda_c^+\pi^+\pi^-$ invariant mass spectrum with different $x_p$ cuts.

In addition to studies of the $\Lambda_c^+$ sideband spectra, a close examination of various reflection sources has shown that the signal cannot be artificially generated. For example, it is possible that a slow pion combined with the final states $\Sigma_c^{++} \to \Lambda_c^+\pi^+$ or $\Sigma_c^0 \to \Lambda_c^+\pi^-$ could lead to a contribution in the signal region. To check this, so-called wrong charge combinations - $\Lambda_c^+\pi^-\pi^-$ and $\Lambda_c^+\pi^+\pi^+$ have been studied. No enhancements in the signal range have been seen in both spectra. A Monte Carlo simulation of the process $e^+e^- \to \Sigma_c X$ supported this conclusion. Multiple counting has also been studied and was found to be negligibly small and distributed uniformily over a wide range of the $\Lambda_c^+\pi^+\pi^-$ invariant mass.

To obtain an upper limit for the natural width, $\Gamma$, of the $\Lambda_c^{*+}$, the signal shape was parametrized using a non-relativistic Breit-Wigner convoluted with a Gaussian resolution function. The width of the Gaussian was fixed to its expected value of 2.6 $MeV/c^2$. The fit yielded an upper limit of $\Gamma < 3.2$ $MeV/c^2$ at the 90% confidence level.

In order to extract the momentum distribution of the signal, the $x_p$ spectrum was divided into five intervals starting from $x_p = 0.5$. The numbers of events were obtained by fitting the invariant $\Lambda_c^+\pi^+\pi^-$ mass spectra in each $x_p$ range using a Gaussian with its width fixed to the Monte Carlo value for the resolution and the mass fixed to the overall measured value, plus a polynomial background. The number in each $x_p$ bin was then corrected for detector efficiency. The procedure was complicated by the fact that the efficiencies differ among the $\Lambda_c^+$ decay modes. These were determined through Monte Carlo simulation and weighted by the respective branching ratios relative to the decay $pK^-\pi^+$. The ARGUS updated measurements of these fractions were used - $0.18 \pm 0.03 \pm 0.04$ [14], $0.55 \pm 0.08 \pm 0.03$ , and $0.69 \pm 0.11 \pm 0.05$ for the $\Lambda^0\pi^+$, $p\overline{K^0}$ and $\Lambda^0\pi^+\pi^+\pi^-$ channels correspondingly. The systematic errors were determined by varying the cuts, the fit functions and ranges, and the widths. This procedure results in the following expression for the efficiency, $\eta(\Lambda_c^+\pi^+\pi^-)$, normalized to the branching ratio of $\Lambda_c^+ \to pK^-\pi^+$:

$$\frac{\eta(\Lambda_c^+\pi^+\pi^-)}{Br(\Lambda_c^+ \to pK^-\pi^+)} = \sum_{i=1}^{4} \frac{Br(\Lambda_c^+ \to X_i)}{Br(\Lambda_c^+ \to pK^-\pi^+)} \cdot \eta(X_i),$$

where the sum is over the modes $pK^-\pi^+$, $\Lambda^0\pi^+$, $\Lambda^0\pi^+\pi^+\pi^-$ and $p\overline{K^0}$. The corrected $x_p$ spectrum is shown in Fig. 2. The overlayed curve corresponds to the fit of the Peterson *et al.*

fragmentation function [13] which has the form

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

The value found for the fragmentation parameter is $\epsilon = 0.044 \pm 0.018$. In comparison, the corresponding $x_p$ distributions of $\Lambda_c^+$ and $\Sigma_c$ baryons are significantly softer with Peterson parameters $\epsilon_{\Lambda_c^+} = 0.24 \pm 0.04$ [15] and $\epsilon_{\Sigma_c} = 0.29 \pm 0.06$ [16], respectively. This might be an indication that the large fraction of $\Lambda_c^+$ and $\Sigma_c$ baryons is produced in decays of higher excited states. The fitted fragmentation function was used to extrapolate the number of events obtained with $x_p > 0.5$ into the whole momentum interval. The rate of $\Lambda_c^+$ production from the $\Lambda_c^{*+}$ through its decay into $\Lambda_c^+\pi^+\pi^-$ was found to be $(4.1 \pm 1.0 \pm 0.8)\%$.

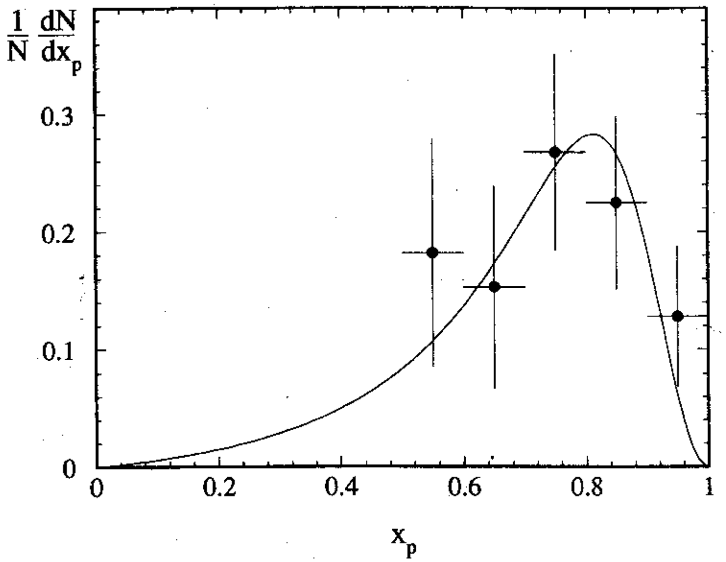


**Figure 2:** The $x_p$ spectrum of the $\Lambda_c^{*+}$. The solid curve is the result of the fit with the Peterson *et al.* fragmentation function.

In order to convert the fitted number of signal events in the $\Lambda_c^+\pi^+\pi^-$ spectrum into a value for the production rate, $\sigma(\Lambda_c^{*+})$, in $e^+e^-$ annihilations at $\sqrt{s} = 10.4\ GeV$ for $x_p > 0.5$, we used the ARGUS measurement of $Br(\Lambda_c^+ \to pK^-\pi^+) = (4.0 \pm 0.3 \pm 0.8)\%$ [17]. This gives $\sigma \cdot Br(\Lambda_c^{*+} \to \Lambda_c^+\pi^+\pi^-) = (9.9 \pm 2.1 \pm 2.2)\ pb$. The quoted systematic error reflects contributions from varying the cut and fit parameters, from uncertainties in the Monte Carlo simulation, and from uncertainties in the $\Lambda_c^+$ branching ratios. Using the Peterson *et al.* fragmentation



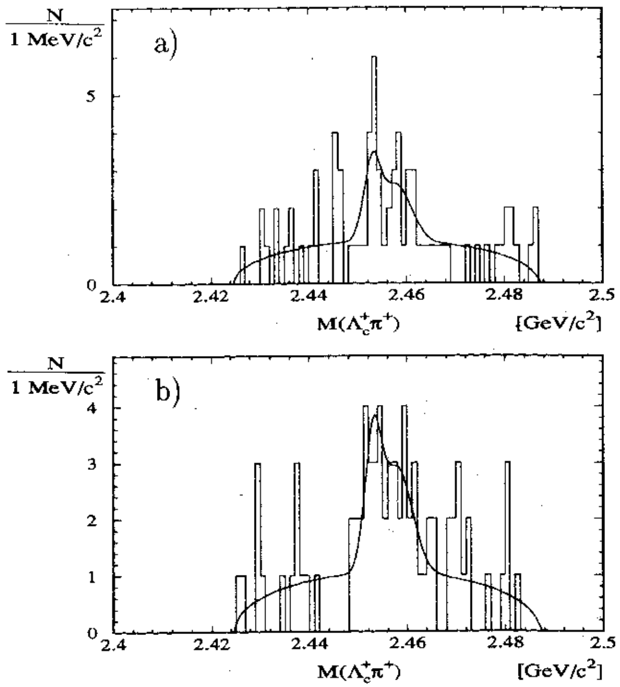


**Figure 3:** The invariant mass distributions for $\Lambda_c^+\pi$ combinations taken from the signal region $(|M(\Lambda_c^+\pi^+\pi^-) - 2627\ MeV/c^2| < 6\ MeV/c^2)$ for a) $\Lambda_c^+\pi^+$, and b)$\Lambda_c^+\pi^-$. The solid curves represent the fits described in the text.

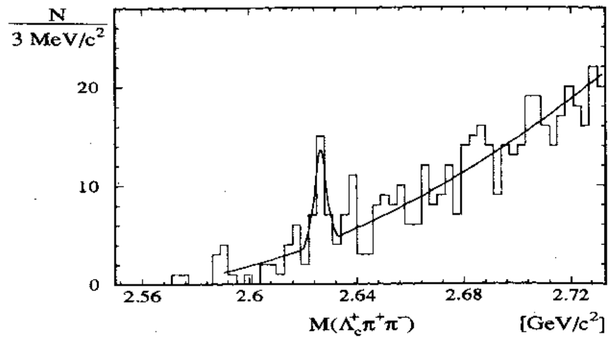


**Figure 4:** The invariant mass distribution for $\Lambda_c^+\pi^+\pi^-$ combinations satisfying both $|M(\Lambda_c^+\pi^+) - M(\Sigma_c^{++})| > 5.1\ MeV/c^2$ and $|M(\Lambda_c^+\pi^-) - M(\Sigma_c^0)| > 5.1\ MeV/c^2$. The solid curve represents the fit described in the text.

parameter $\epsilon$ derived from the fit we extrapolated to zero momentum and found

$$\sigma \cdot Br(\Lambda_c^{*+} \to \Lambda_c^+\pi^+\pi^-) = (11.5 \pm 2.5 \pm 3.0)\ pb.$$

Three possible decay channels could contribute to the observed signal: non-resonant $\Lambda_c^+\pi^+\pi^-$ production, $\Sigma_c^{++}\pi^-$ and $\Sigma_c^0\pi^+$, followed by $\Sigma_c \to \Lambda_c^+\pi^\pm$. Monte Carlo studies indicate that the mass resolutions and efficiencies for all three channels are approximately the same.

The resonant contribution has been determined by studying the invariant mass spectra of $\Lambda_c^+\pi^\pm$ combinations taken from the signal region, defined as $|M(\Lambda_c^+\pi^+\pi^-) - 2627\ MeV/c^2| < 6\ MeV/c^2$. The mass distributions for the $\Lambda_c^+\pi^+$ and $\Lambda_c^+\pi^-$ are shown in Fig.3a and Fig.3b, respectively. Enhancements around the $\Sigma_c^{++}$ and $\Sigma_c^0$ masses [12] can be seen. The phase space for decays into $\Sigma_c^{++}\pi^-$ and $\Sigma_c^0\pi^+$ is limited for the candidate $\Lambda_c^{*+}$ resonance, so one expects a rather narrow contribution from the $\Sigma_c^0\pi^+$ channel in the $\Lambda_c^+\pi^+$ mass spectrum and from the $\Sigma_c^{++}\pi^-$ channel in the $\Lambda_c^+\pi^-$ spectrum. For example consider $\Lambda_c^{*+} \to \Sigma_c^0\pi^+$, followed by $\Sigma_c^0 \to \Lambda_c^+\pi^-$. $\Lambda_c^+$ baryons picking up a primary $\pi^+$ produce a bump in the $\Lambda_c^+\pi^+$ distribution. Based on Monte Carlo studies, the "$\Sigma_c^0$" signal in the $\Lambda_c^+\pi^+$ mass spectrum is expected to have a mass around 2458 $MeV/c^2$ and a resolution of about 3 $MeV/c^2$. Consequently, the spectra shown in Fig.3a and Fig.3b were fit with a constant term multiplied by square-root threshold factors to describe the background, and two Gaussians to represent the resonant contribution. The first Gaussian served to parametrize the $\Sigma_c$ signal; its width was fixed to the Monte Carlo determined detector resolution 1.7 $MeV/c^2$, and its position was fixed to the $\Sigma_c$ mass [12]. The second Gaussian was added in order to take into account the above mentioned cross talk between resonant channels. Its width and position were also fixed to the values determined from Monte Carlo. The resulting number of resonant events obtained in fitting the spectrum in Fig. 3a is $19.5 \pm 6.2$ while fit to the $\Lambda_c^+\pi^-$ distribution resulted in $22.7 \pm 6.7$ events.

The non-resonant contribution was estimated by removing all $\Lambda_c^+\pi$ combinations having an invariant mass within 5.1 $MeV/c^2$ ($3.0\sigma$) of the $\Sigma_c$ mass, i.e. requiring

$$\left|M(\Lambda_c^+\pi^+) - M(\Sigma_c^{++})\right| > 5.1\ MeV/c^2 \text{ and } \left|M(\Lambda_c^+\pi^-) - M(\Sigma_c^0)\right| > 5.1\ MeV/c^2$$

simultaneously. The resulting $\Lambda_c^+\pi^+\pi^-$ spectrum is shown in Fig.4. This was fit with a Gaussian plus second order polynomial, resulting in $16.2 \pm 6.1$ events.

Using these results the following fractions have been obtained:

$$\frac{Br(\Lambda_c^{*+} \to \Sigma_c\pi^\pm)}{Br(\Lambda_c^{*+} \to \Lambda_c^+\pi^+\pi^-)} = 0.46 \pm 0.14$$

$$\frac{Br(\Lambda_c^{*+} \to (\Lambda_c^+\pi^+\pi^-)_{nr})}{Br(\Lambda_c^{*+} \to \Lambda_c^+\pi^+\pi^-)} = 0.54 \pm 0.14.$$

Two species of charmed baryons can decay with $\Lambda_c^+\pi^+\pi^-$ in the final state. These are $\Lambda_c^{*+}$ and $\Sigma_c^{*+}$. Unfortunately, we cannot determine directly the quantum numbers of the observed resonance. However, model calculations predict substantially higher masses for excited $\Sigma_c^*$



| $J^P$ | $\Lambda_c^*$ | $\Sigma_c^*$ |
|---|---|---|
| $\frac{1}{2}^-$ | 2630 $MeV/c^2$ | 2765 $MeV/c^2$ |
| $\frac{3}{2}^-$ | 2640 $MeV/c^2$ | 2770 $MeV/c^2$ |

**Table 2**: Theoretical predictions for the masses of excited charmed baryons.

states, while predictions for P-wave $\Lambda_c^{*+}$ states lie close to our measured value. Theoretical estimates for the masses of the lowest lying excited charmed baryons are given in Table 2 [9].

In summary we have observed a new charmed baryon resonance in the $\Lambda_c^+\pi^+\pi^-$ system. The mass of the state was measured to be $(2626.6 \pm 0.5 \pm 1.5)\ MeV/c^2$ and the natural width was estimated to be less than 3.2 $MeV/c^2$ at a 90% confidence level. The production rate times branching ratio into the above channel was found to be $(11.5 \pm 2.5 \pm 3.0)\ pb$.

**Acknowledgements**

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