Physics Letters B 317 (1993) 227–232
North-Holland

PHYSICS LETTERS B

Observation of a new charmed baryon

ARGUS Collaboration

H. Albrecht, H. Ehrlichmann, T. Hamacher, R.P. Hofmann, T. Kirchhoff, A. Nau, S. Nowak [1], H. Schröder, H.D. Schulz, M. Walter [1], R. Wurth

DESY, Hamburg, Germany

C. Hast, H. Kapitza, H. Kolanoski, A. Kosche, A. Lange, A. Lindner, R. Mankel, M. Schieber, T. Siegmund, B. Spaan, H. Thurn, D. Töpfer, D. Wegener

Institut für Physik[2], Universität Dortmund, Germany

M. Bittner, P. Eckstein

Institut für Kern- und Teilchenphysik[3], Technische Universität Dresden, Germany

M. Paulini, K. Reim, H. Wegener

Physikalisches Institut[4], Universität Erlangen-Nürnberg, Germany

R. Eckmann, R. Mundt, T. Oest, R. Reiner, W. Schmidt-Parzefall

II. Institut für Experimentalphysik, Universität Hamburg, Germany

J. Stiewe, S. Werner

Institut für Hochenergiephysik[5], Universität Heidelberg, Germany

K. Ehret, W. Hofmann, A. Hüpper, S. Khan, K.T. Knöpfle, M. Seeger, J. Spengler

Max-Planck-Institut für Kernphysik, Heidelberg, Germany

D.I. Britton [6], C.E.K. Charlesworth [7], K.W. Edwards [8], E.R.F. Hyatt [6], P. Krieger [7], D.B. MacFarlane [6], P.M. Patel [6], J.D. Prentice [7], P.R.B. Saull [6], K. Tzamariudaki [6], R.G. Van de Water [7], T.-S. Yoon [7]

Institute of Particle Physics[9], Canada

D. Reßing, M. Schmidtler, M. Schneider, K.R. Schubert, K. Strahl, R. Waldi, S. Weseler

Institut für Experimentelle Kernphysik[10], Universität Karlsruhe, Germany

G. Kernel, P. Križan, E. Križnič, T. Podobnik, T. Živko

Institut J. Stefan and Oddelek za fiziko[11], Univerza v Ljubljani, Ljubljana, Slovenia

V. Balagura, I. Belyaev, S. Chechelnitsky, M. Danilov, A. Droutskoy, Yu. Gershtein, A. Golutvin, I. Korolko, G. Kostina, D. Litvintsev, V. Lubimov, P. Pakhlov, S. Semenov,

A. Snizhko, I. Tichomirov and Yu. Zaitsev

Institute of Theoretical and Experimental Physics, Moscow, Russia

Received 20 August 1993
Editor: K. Winter

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 $\Lambda_c^+\pi^+\pi^-$. (All references to a specific charged state also imply the charge conjugate state.) 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 Λ_c^+ in e^+e^- annihilations was first observed by the MARK II Collaboration [1], followed by the neutral and doubly charged isospin partners Σ_c^0 and Σ_c^{++} of the Σ_c isotriplet observed by the ARGUS [2] collaboration, and the Ξ_c^0 and Ξ_c^+, seen by the CLEO [3] and ARGUS [4] collaborations. Last year the ARGUS collaboration reported the first evidence for the doubly strange charmed baryon Ω_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 Λ_c^{*+} in the final state $\Lambda_c^+\pi^+\pi^-$. This choice of channel is justified because an excited Λ_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 4π 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 θ in the range $|\cos(\theta)| < 0.92$, and momenta transverse to the beam direction greater than 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 Λ_c^+ as well as to suppress possible reflections from charmed mesons to a negligible level. Λ^0 (K_S^0) candidates were defined as $p\pi^-$ $(\pi^+\pi^-)$

[1] DESY, IfH Zeuthen.
[2] Supported by the German Bundesministerium für Forschung und Technologie under contract number 054DO51P.
[3] Supported by the German Bundesministerium für Forschung und Technologie, under contract number 055DD11P.
[4] Supported by the German Bundesministerium für Forschung und Technologie under contract number 054ER12P.
[5] Supported by the German Bundesministerium für Forschung und Technologie under contract number 055HD21P.
[6] McGill University, Montreal, Quebec, Canada.
[7] University of Toronto, Toronto, Ontario, Canada.
[8] Carleton University, Ottawa, Ontario, Canada.
[9] Supported by the Natural Sciences and Engineering Research Council Canada.
[10] Supported by the German Bundesministerium für Forschung und Technologie under contract number 054KA17P.
[11] Supported by the Department of Science and Technology of the Republic of Slovenia and the Internationales Büro KfA, Jülich.

pairs forming secondary vertices. A mass constraint fit was applied to each combination having an invariant mass within ± 10 (± 30) MeV/c^2 of the nominal Λ^0 (K_S^0) mass [12], and those with a χ^2 of less than 25 were used in the subsequent analysis. In addition the angle α between the Λ^0 (K_S^0) 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 Λ_c^+ baryon was reconstructed in four decay modes – $pK^-\pi^+$, pK_S^0, $\Lambda^0\pi^+$, and $\Lambda^0\pi^+\pi^+\pi^-$. Each combination with an invariant mass lying within ± 25 MeV/c^2 for $pK^-\pi^+$ and $\Lambda^0\pi^+\pi^+\pi^-$, ± 30 MeV/c^2 for pK_S^0 and ± 40 MeV/c^2 for $\Lambda^0\pi^+$ of the nominal Λ_c^+ mass [12] was subjected to a mass constraint fit to improve the momentum resolution.

Every Λ_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 $p_{\max} = \sqrt{E_{\text{beam}}^2 - M^2(\Lambda_c^+\pi^+\pi^-)}$.

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 Λ_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

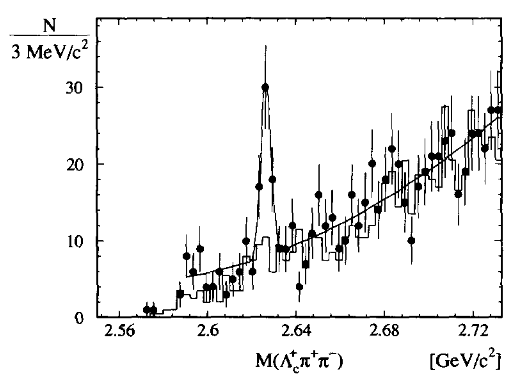

Fig. 1. Invariant mass distribution for all accepted $\Lambda_c^+\pi^+\pi^-$ combinations. The solid histogram results from using the Λ_c^+ sidebands.

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

$x_p >$	Mass (MeV/c^2)	σ(MeV/c^2)	Entries
0.4	2626.7 ± 0.6	2.3 ± 0.5	45.6 ± 10.1
0.5	2626.6 ± 0.5	2.2 ± 0.5	42.4 ± 8.8
0.6	2626.7 ± 0.5	2.1 ± 0.4	34.9 ± 7.5

a Gaussian with free width and position to represent the signal. The fit resulted in 42.4 ± 8.8 events at a mass of (2626.6 ± 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 ± 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.

In addition to studies of the Λ_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, Γ, of the Λ_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 Λ_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 – $0.18 \pm 0.03 \pm 0.04$ [13], $0.55 \pm 0.08 \pm 0.03$, 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 $\Lambda_c^+ \to pK^-\pi^+$:

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

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 [14] which has the form

$$\frac{\mathrm{d}N}{\mathrm{d}x_p} \propto x_p^{-1}\left[1 - \frac{1}{x_p} - \frac{\epsilon}{1-x_p}\right]^{-2}.$$

The value found for the fragmentation parameter is $\epsilon = 0.044 \pm 0.018$. In comparison, the corresponding x_p distributions of Λ_c^+ and Σ_c baryons are significantly

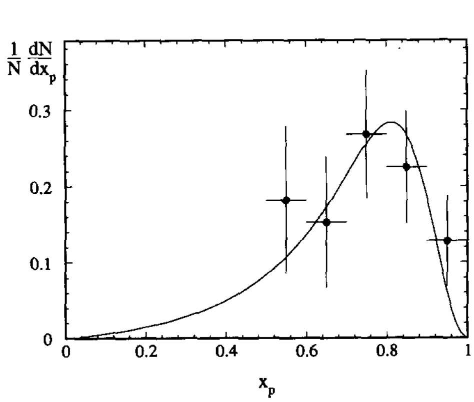

Fig. 2. The x_p spectrum of the Λ_c^{*+}. The solid curve is the result of the fit with the Peterson et al. fragmentation function.

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 Λ_c^+ and Σ_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 Λ_c^+ production from the Λ_c^{*+} through its decay into $\Lambda_c^+\pi^+\pi^-$ was found to be $(4.1 \pm 1.0 \pm 0.8)\%$.

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 $\mathrm{Br}(\Lambda_c^+ \to pK^-\pi^+) = (4.0 \pm 0.3 \pm 0.8)\%$ [17]. This gives $\sigma \cdot \mathrm{Br}(\Lambda_c^{*+} \to \Lambda_c^+\pi^+\pi^-) = (9.9 \pm 2.1 \pm 2.2)$ 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 Λ_c^+ branching ratios. Using the Peterson et al. fragmentation parameter ϵ derived from the fit we extrapolated to zero momentum and found

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

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 $|M(\Lambda_c^+\pi^+\pi^-) - 2627\ \mathrm{MeV}/c^2| < 6\ \mathrm{MeV}/c^2$. The mass distributions for the $\Lambda_c^+\pi^+$ and $\Lambda_c^+\pi^-$ are shown in fig. 3a and fig. 3b, respectively. Enhancements around the Σ_c^{++} and Σ_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 Λ_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 $\Sigma_c^0 \to \Lambda_c^+\pi^-$. Λ_c^+ baryons picking up a primary π^+ produce a bump in the $\Lambda_c^+\pi^+$ distribution. Based on Monte Carlo studies, the "Σ_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 Σ_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 Σ_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 ± 6.2 while fit to the $\Lambda_c^+\pi^-$ distribution resulted in 22.7 ± 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 (3.0σ) of the Σ_c mass, i.e. requiring

$$|M(\Lambda_c^+\pi^+) - M(\Sigma_c^{++})| > 5.1\ \mathrm{MeV}/c^2,$$

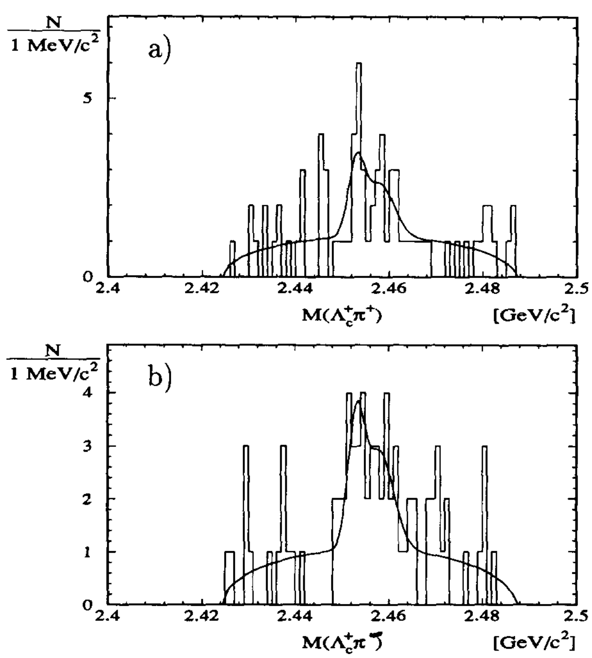

Fig. 3. The invariant mass distributions for $\Lambda_c^+\pi$ combinations taken from the signal region ($|M(\Lambda_c^+\pi^+\pi^-) - 2627\ \mathrm{MeV}/c^2| < 6\ \mathrm{MeV}/c^2$) for (a) $\Lambda_c^+\pi^+$, and (b) $\Lambda_c^+\pi^-$. The solid curves represent the fits described in the text.

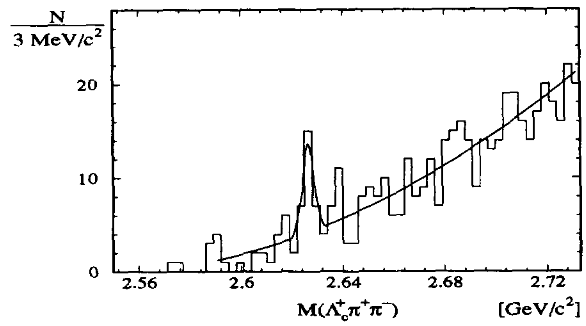

Fig. 4. The invariant mass distribution for $\Lambda_c^+\pi^+\pi^-$ combinations satisfying both $|M(\Lambda_c^+\pi^+) - M(\Sigma_c^{++})| > 5.1\ \mathrm{MeV}/c^2$ and $|M(\Lambda_c^+\pi^-) - M(\Sigma_c^0)| > 5.1\ \mathrm{MeV}/c^2$. The solid curve represents the fit described in the text.

$$|M(\Lambda_c^+\pi^-) - M(\Sigma_c^0)| > 5.1\ \mathrm{MeV}/c^2,$$

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 ± 6.1 events.

Using these results the following fractions have been obtained:

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

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

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

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

J^P	Λ_c^* (MeV/c^2)	Σ_c^* (MeV/c^2)
$\frac{1}{2}^-$	2630	2765
$\frac{3}{2}^-$	2640	2770

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.

It is a pleasure to thank U. Djuanda, E. Konrad, E. Michel and W. Reinsch for their competent technical help in running the experiment and processing the data. We thank Dr. H. Nesemann, B. Sarau, and the DORIS group for the excellent operation of the storage ring. The visiting groups wish to thank DESY directorate for the support and kind hospitality extended to them.

References

[1] MARK II Collab., G.S. Abrams et al., Phys. Rev. Lett. 44 (1980) 10.
[2] ARGUS Collab., H. Albrecht et al., Phys. Lett. B 211 (1988) 489.
[3] CLEO Collab., P. Avery et al., Phys. Rev. Lett. 62 (1989) 863;
CLEO Collab., M.S. Alam et al., Phys. Lett.. B 226 (1989) 401.
[4] ARGUS Collab., H. Albrecht et al., Phys. Lett. B 247 (1990) 121.
[5] ARGUS Collab., H. Albrecht et al., Phys. Lett. B 288 (1992) 367.
[6] A. De Rújula, H. Georgi and S.L. Glashow, Phys. Rev. D 12 (1975) 147.
[7] N. Isgur and G. Karl, Phys. Lett. B 74 (1978) 353.
[8] L.A. Copley N. Isgur and G. Karl, Phys. Rev.D 20 (19179) 768.
[9] S. Capstick and N. Isgur, Phys. Rev. D 34 (1986) 2809.
[10] C.S. Kalman and B. Tran, Nuovo Cim. A 102 (1989) 835.
[11] ARGUS Collab., H. Albrecht et al., Nucl. Instr. and Methods A 275 (1989) 1.
[12] Particle Data Group, Review of Particle Properties, Phys. Lett. B 239 (1992) 1.
[13] ARGUS Collab., H. Albrecht et al., Phys. Lett. B 274 (1992) 239.
[14] C. Peterson et al., Phys. Rev. D 27 (1983) 105.
[15] C.E.K. Charlesworth, A Study of the Decay Properties of the Charmed Baryon Λ_c^+, Ph.D. thesis, University of Toronto (1992).
[16] ARGUS Collab., H. Albrecht et al., Phys. Lett. 207B (1988) 489.
[17] ARGUS Collab., H. Albrecht et al., Z. Phys. C 56 (1992) 1.