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Evidence for the production of the charmed, doubly strange baryon Ω_c in e^+e^- annihilation

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Using the detector ARGUS at the storage ring DORIS II of DESY, we have found evidence for the production of the charmed and doubly strange baryon Ω_c through its decay channel $\Xi^- K^- \pi^+ \pi^+$. Its mass has been determined to be $(2719.0 \pm 7.0 \pm 2.5)$ MeV/c^2, and the product of production cross section and branching ratio into the above channel to be $(2.41 \pm 0.90 \pm 0.30)$ pb.

Following the discovery of the J/ψ particle in 1974 which was interpreted as the bound state of a charmed quark and its antiquark, the existence of hadrons with charm as an open flavour has been postulated and experimentally proven. For charmed baryons, an early prediction of masses was published in a classical pioneering paper by DeRujula, Georgi and Glashow [1]. Production of the Λ_c in e^+e^- annihilations was first observed by the MARK II Collaboration [2], the neutral and doubly charged isospin partners Σ_c^0 and Σ_c^{++} of the Σ_c isotriplet have been observed by the ARGUS Collaboration [3], and the charged and neutral Ξ_c's have been seen by the CLEO [4] and ARGUS [5] Collaborations. The Ω_c, the charmed isospin singlet in the spin $-\frac{1}{2}$ baryon multiplet, has up to now not yet been observed in e^+e^- annihilations. The first evidence for its existence was obtained in 1985 by the WA-62 Collaboration who found a cluster of three events in the spectrum of the $(\Xi^- K^- \pi^+ \pi^+)$ invariant mass with a mean and spread of (2740 ± 20) MeV/c^2 [6].

The Ω_c baryon is supposed to contain one charmed and two strange quarks. In the framework of Cabibbo allowed spectator decays, its weak decay is expected to lead to a neutral final state with baryon number equal to one, and strangeness equal to -3. One such possible final state consists of a Ξ^-, a K^-, and two positive pions.

The Ω_c has been searched for in this decay channel, where the Ξ^- is observed in its decay mode [#1] to $\Lambda\pi^-$. The signal described here has been observed in multihadron events produced in e^+e^- annihilations at the energy of the $\Upsilon(4S)$ resonance and in the nearby continuum, corresponding in total to an integrated luminosity of 389 events/pb. A detailed description of the detector ARGUS and its particle identification capabilities can be found in ref. [7].

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 through measurement of their specific energy loss dE/dx in the drift chamber gas, and their velocities in the time-of-flight system. The informations from these devices are combined into a likelihood ratio for each track. All tracks with a likelihood ratio exceeding 0.01 for the kaon, pion and proton hypotheses, and with a χ^2 con-

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[#1] In this paper, references to a specific charge state should be taken to imply the charge-conjugate state, too.

tributing to the vertex reconstruction of less than 36, were accepted. A detailed description of the ARGUS particle identification algorithms is given in ref. [7].

Λ hyperons to be used in the search were reconstructed from their decays to protons and pions forming well identified secondary vertices. Λ candidates with a proton–pion invariant mass within ±12 MeV/c^2 of the nominal Λ mass [8], and a χ^2 for the Λ mass hypothesis of less than 25, were subjected to a mass constraint fit. The $(\Lambda\pi^-)$ invariant mass spectrum with the Ξ^- signal is shown in fig. 1. A fit to the Ξ^- peak gives a mass of (1321.3±0.3) MeV/c^2, in agreement with the PDG value [8]. To those $\Lambda\pi^-$ combinations with an invariant mass of ±12 MeV/c^2 of the nominal Ξ^- mass [8], and a χ^2 of less than 25 for the Ξ^- mass hypothesis, another mass constraint fit was applied. For the pion from the Ξ^- decay no restriction of the χ^2 contributing to the main vertex reconstruction was required.

In e^+e^- annihilation processes, charmed hadrons are expected to be produced in the fragmentation of the primary charm quarks. Thus, their momentum spectra are expected to be hard. This kinematical property is generally used to suppress background from soft hadronization processes by applying cuts to the scaled momentum $x_p = p/p_{\max}$, where $p_{\max} = \sqrt{E_{\text{beam}}^2 - M^2}$, with p and M being momentum and invariant mass of the particle combination under consideration.

The hypothesis that charmed hadrons originate from primary charm quark jets leads to another expectation, namely that their decay products be collimated around the charm quark direction. Since this direction cannot be exactly reconstructed from the hadrons experimentally observed, it is approximated as the event thrust axis. Cuts in the angles between decay particle momenta and the thrust axis will most likely allow an additional reduction of background from soft fragmentation.

In searching for the Ω_c signal, we exploit both these kinematical properties in order to achieve a maximum background reduction. The signal we look for is expected to be rather weak when compared with the lighter charmed baryons, due to the suppression of strange quark production in the fragmentation process. Furthermore, the growing mass of the light diquark accompanying the charmed quark leads to a softening of the momentum spectrum, as observed experimentally comparing Λ_c and Ξ_c, and as predicted e.g. by the model of Peterson et al. [9].

Finally, we take into account that Λ hyperons from Ω_c to Ξ^- to Λ cascades decay after sizeable distances from the primary vertex. We therefore apply a cut in the decay length of the Λ hyperon to suppress back-

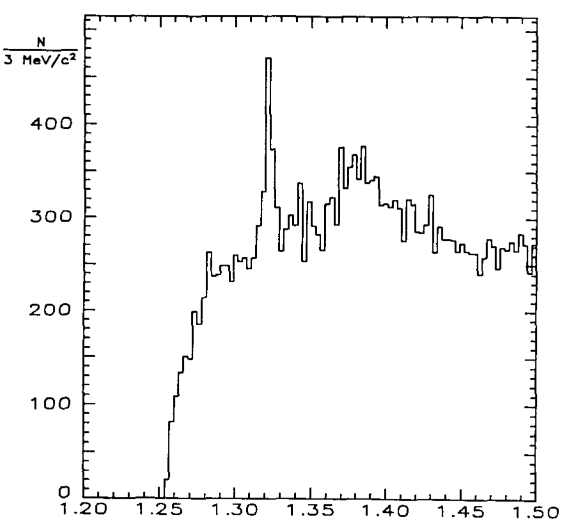

Fig. 1. Invariant $(\Lambda\pi^-)$ mass spectrum showing the Ξ^- signal.

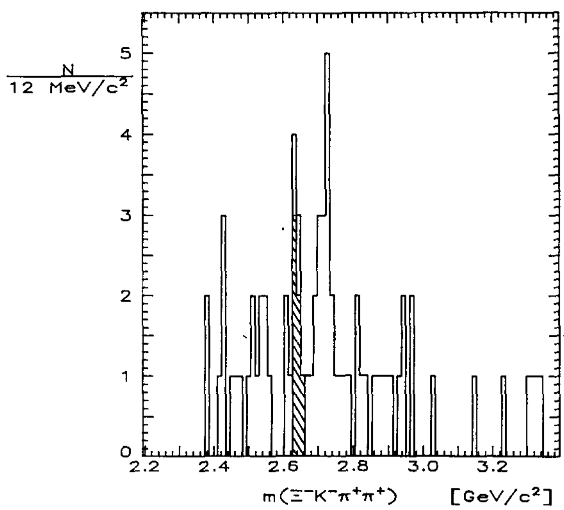

Fig. 2. Invariant $(\Xi^-K^-\pi^+\pi^+)$ mass spectrum, after applying the cuts described in the text; the hatched region shows the reflection from the Ξ_c^0 decay.

ground from directly produced Λ's, and to work in a region with well controlled acceptance.

The distribution of the invariant mass of the $\Xi^-K^-\pi^+\pi^+$ system is shown in fig. 2, where the distance between primary vertex and Λ decay vertex was required to be larger than 4 cm. The scaled momentum x_p was larger than 0.4. All decay particle momenta were required to point into the same "hemisphere", the hemispheres being defined by a plane perpendicular to the thrust axis. The cosine of the Ξ^- momentum vector with respect to the axis pointing into the selected hemisphere was required to be larger than 0.5. A study of Monte Carlo generated events shows that one loses about 40% of entries in the signal region. The background, however, is reduced by more than 80%. Cross checking this procedure with the signal from the decay $\Xi_c^0 \to \Xi^-\pi^+\pi^+\pi^-$ proves its background reducing power.

The figure shows two small peaks close to each other. The lower one around 2.6 GeV/c^2 can be attributed to a reflection from the decay $\Xi_c^0 \to \Xi^-\pi^+\pi^+\pi^-$, where the π^- is misidentified as a K^-. This follows from analyzing Monte Carlo generated Ξ_c^0 decays, but can also be proven using the Ξ_c^0 signal in our data sample: after applying the kinematical cuts described above and cutting a ± 22 MeV/c^2 wide slice around the Ξ_c^0 peak in the $\Xi^-\pi^+\pi^+\pi^-$ mass distribution, one subjects this particle combination to the selection procedure applied in the Ω_c search. The result is a rather narrow peak in the $\Xi^-K^-\pi^+\pi^+$ invariant mass distribution which fits the low mass peak observed in fig. 2 (hatched region). Consequently, this satellite peak from the reflecting Ξ_c^0 is subtracted from the mass distributions discussed in the rest of the paper. Fig. 3 shows the distribution corresponding to the one displayed in fig. 2, after subtraction of the satellite peak.

The remaining signal is located at a mass of about 2720 MeV/c^2. A maximum likelihood fit to the mass spectrum, with a gaussian on top of a flat background, yields a mass value of (2719.0 ± 7.0) MeV/c^2, and a width of $\sigma = (16.6 \pm 6.3)$ MeV/c^2. This is in good agreement with the width derived from Monte Carlo generated events which is (13.5 ± 2.6) MeV/c^2. The number of entries in the peak is 11.5 ± 4.3.

We now apply another two weak cuts in order to further remove combinatorial background: we demand the normalized likelihood for the kaon hypothesis to exceed 2%, and we require a charged multiplicity of larger than 10. The latter cut is motivated by the observation that events containing a $(\Xi^-K^-\pi^+\pi^+)$ combination are forced towards higher multiplicities. The invariant mass distribution, after these additional cuts, is shown in fig. 4. Fitting the spectrum, with a background function plus a gauss-

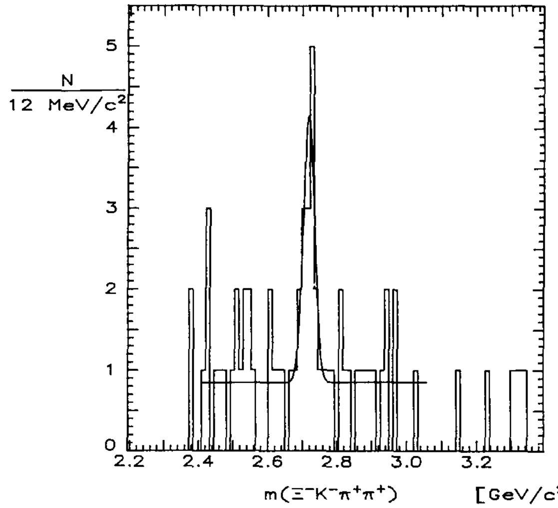

Fig. 3. Invariant $(\Xi^-K^-\pi^+\pi^+)$ mass spectrum as above, after subtracting the reflection from the Ξ_c^0 decay. The full curve shows the result of the fit.

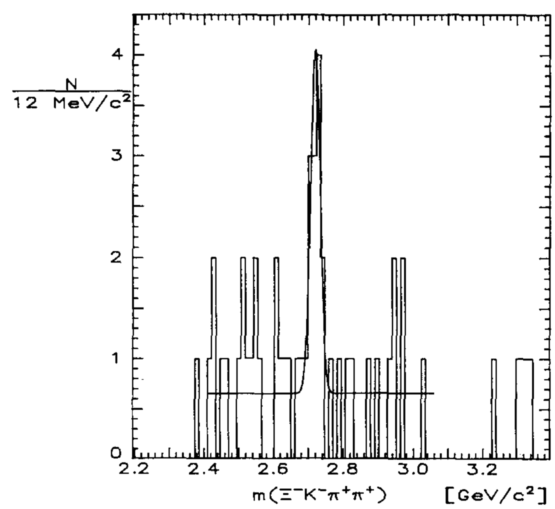

Fig. 4. Invariant $(\Xi^-K^-\pi^+\pi^+)$ mass spectrum, after applying additional cuts on kaon likelihood and multiplicity (see text). The full curve shows the result of the fit.

ian as described above, yields 9.9 ± 3.8 entries in the peak, a mass value of (2719 ± 6) MeV/c^2, and a width of $\sigma = (13.8 \pm 4.9)$ MeV/c^2.

The statistical significance of the Ω_c signal displayed in fig. 4 can be estimated in the following way: First, we define a $\pm 3\sigma$ region around the position of the peak where we integrate the background contribution. We then perform a conservative background estimation: we fit the spectrum assuming that there is no signal at all, i.e. using a background shape alone. This leaves us with 5.6 background entries in the signal region. Adding up all entries in the signal region, we arrive at 14 events. We then calculate, using poissonian statistics, the probability that the background produces the signal as a statistical fluctuation, and arrive at a value of 2.0×10^{-3}. When we start from the background level resulting from the fit with a gaussian plus background shape, we get 4.4 background entries in the signal region, corresponding to a probability of 2.0×10^{-4}.

Using a different background parametrization, i.e. a second order polynomial modified by a function describing the threshold behaviour, does not change the results on mass, width and significance.

In order to demonstrate that the signal is neither a fluctuation of the combinatorial background, nor artificially generated, we have performed a series of tests:

First, we have investigated the behaviour of the signal with respect to mass and width fitted when we apply successive x_p cuts. Additional cuts have been imposed as for the spectrum shown in fig. 4. The results are compiled in table 1. We conclude that the signal, in mass and width, is stable against a variation of the x_p cut.

Second, we have performed checks whether the signal could be due to a kinematical reflection. As a potential source we regard the Λ_c in its decay channel $\Lambda\pi^+\pi^+\pi^-$, with one pion misidentified as a K^-, and an additional pion being close in phase space to the Λ, so that the $\Lambda\pi^-$ combination is mistaken for a Ξ^-. We have checked this possibility using Monte Carlo generated Λ_c's as well as the $\Lambda_c \to \Lambda\pi^+\pi^+\pi^-$ signal visible in our data. No structure in the signal region is observed.

Table 1
Mass and width for the Ω_c signal obtained from fits with different x_p cuts.

$x_p >$	Mass (MeV/c^2)	σ (MeV/c^2)	Entries
0.0	2719 ± 7.0	13.5 (fixed through MC)	10.2 ± 4.0
0.2	2719 ± 7.0	13.5 (fixed through MC)	10.2 ± 4.0
0.4	2719 ± 6.0	13.8 ± 4.9	9.9 ± 3.6
0.5	2716 ± 6.0	10.9 ± 4.9	7.3 ± 3.1

The second potential source, the decay $\Xi_c^0 \to \Xi^-\pi^-\pi^-\pi^+$, has been discussed above and shown to result in a satellite peak below the Ω_c signal in the $\Xi^-K^-\pi^+\pi^+$ mass distribution (see fig. 2).

We have finally tested the possibility that the signal is generated by accidental kinematical correlations. This was done in two different ways: First, we have investigated the so called "wrong charge combination", i.e. a combination of particles kinematically equivalent to the relevant one, but excluding a physical signal due to the mismatch of quantum numbers. Here, we have investigated the combination $\Xi^+K^-\pi^+\pi^+$, i.e. subjecting it to the same sequence of cuts as used in detecting the signal. No enhancement in the Ω_c-mass region is observed. Second, we have generated artificial Ξ^-'s by taking $\Lambda\pi^-$ combinations from the upper and lower sidebands of the Ξ^- hyperon, each 25 MeV/c^2 wide, a 24 MeV/c^2 wide region around the real Ξ^- being excluded as the signal region. Repeating our analysis with these artificial Ξ^-'s, we again do not find any structure in the signal region.

The Ω_c signal is visible even without applying an x_p cut. A fit, with the remaining cuts being the same as used for fig. 3, yields 12.2 ± 4.5 entries, allowing us to calculate the product of production cross section and branching ratio, σBR, into the decay channel considered here without applying extrapolation algorithms. This is, however, true only if we can exclude that a sizeable fraction of the low momentum Ω_c's is generated in the decays of B mesons. In order to justify this hypothesis, we have looked into our sample of $\Xi_c^0 \to \Xi^-\pi^-\pi^+\pi^+$ where we expect a similar situation. Here, after extrapolation from $x_p = 0.5$ to $x_p = 0$ with the help of the Peterson fragmentation function, we obtain a σBR of $(2.55 \pm 0.64 \pm 0.39)$ pb [5]; calculating this value without applying an x_p cut, we get $\sigma\mathrm{BR} = (2.40 \pm 0.68)$ pb, in good agreement with the extrapolated number. We conclude that potential contributions from B meson decays can be neglected. If this is the case for the Ξ_c, it is likely to be true for the Ω_c which needs another s-quark to be created in its hadronization. With this assumption we arrive at a σBR for the production of the Ω_c and its subsequent decay into $\Xi^- K^- \pi^+ \pi^+$ of (2.41 ± 0.90) pb. The acceptance for detecting this final state with ARGUS, as determined in a Monte Carlo simulation procedure, is 1.3%.

The error on σBR receives a systematic contribution from variations in the fitting procedure, and uncertainties on the acceptance, which is estimated to be ± 0.30 pb. The systematic error on the mass value measured for the Ω_c gets a contribution from the uncertainty on the ARGUS mass scale which is estimated to be ± 1.2 MeV/c^2 [5], and one from varying the cuts and background shapes in the fitting procedure, which is estimated to be ± 2.0 MeV/c^2.

In summary, we have obtained evidence for the production of the charmed, doubly strange baryon Ω_c in e^+e^- annihilation around 10 GeV. The Ω_c mass is measured to be $(2719.0 \pm 7.0 \pm 2.5)$ MeV. For the product of cross section times branching ratio into the decay channel $\Xi^- K^- \pi^+ \pi^+$, we get a value of $(2.41 \pm 0.90 \pm 0.30)$ pb.

Charmed baryon masses are an important input to theory which has made great progresses in predicting absolute masses. Predictions for the mass of the Ω_c vary between 2680 MeV/c^2 [1], and 2773 MeV/c^2 (Chan, see ref. [10]). Ref. [10] contains a selection of theoretical papers on charmed baryon masses. The present knowledge on charmed baryons, both theoretical and experimental, is reviewed in ref. [11].

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