FIRST MEASUREMENT OF THE LIFETIME
OF THE CHARMED STRANGE BARYON Ξ_c^0

(ACCMOR Collaboration)

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ABSTRACT

We have observed four unambiguous decays of the charmed strange baryon Ξ_c^0 in the NA32 experiment at CERN. Charge-coupled devices and silicon microstrip detectors were used to reconstruct the decay mode $\Xi_c^0 \rightarrow pK^-\bar{K}^*(892)^0$ seen in events produced by the interaction of 230 GeV/c negative pions and kaons on a copper target. We present the first measurement of the lifetime of the Ξ_c^0 , together with a determination of its mass and production cross-section. The resonant components of the Ξ_c^0 decay are studied. We use our earlier measurement of the mass of the Ξ_c^+ in the determination of the isospin mass splitting of the Ξ_c states.

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1. INTRODUCTION

For more than ten years now, many experiments have studied the properties of charmed mesons. The situation regarding charmed baryons is much less clear and it is only recently that experiments have been able to make progress in this difficult subject. Four charmed baryons are expected to decay weakly : $\Lambda_c^+(cud)$, $\Xi_c^+(csu)$, $\Xi_c^0(csd)$ and $\Omega_c^0(css)$. Only the first two appear in the Stable Particle Table of the latest Review of Particle Properties [1]. The Λ_c^+ is well established; we have recently published a measurement of its mass and lifetime [2]. The Ξ_c^+ was first observed by the hyperon beam WA62 experiment at CERN [3] and subsequently confirmed by the E400 experiment at FNAL [4].

More recently, we have reported the observation of two new decay modes of the Ξ_c^+ ($\Xi^- \pi^+ \pi^+$ and $\Sigma^+ K^- \pi^+$)* and measured its mass and lifetime to be $2466.5 \pm 2.7 \pm 1.2$ MeV/c² and $(2.0 \pm 1.1) \cdot 10^{-13}$ s respectively [5]. The CLEO Collaboration has published a year ago the first observation of Ξ_c^0 (decaying to $\Xi^- \pi^+$) [6] and also confirmed the $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ decay mode [7]. They have measured the masses of the Ξ_c^+ and Ξ_c^0 to be $2467 \pm 3 \pm 5$ MeV/c² and $2472 \pm 3 \pm 4$ MeV/c² respectively and the isospin mass splitting $M(\Xi_c^+) - M(\Xi_c^0)$ to be $-5 \pm 4 \pm 1$ MeV/c². In this letter we present data confirming the existence of the Ξ_c^0 , seen in a new decay mode $pK^- \bar{K}^*(892)^0$, and measure its lifetime for the first time.

The data was taken at the CERN SPS in 1985-86 and was a continuation of the 1984 NA32 experiment [8]. The main aim of this new phase was to study the hadroproduction and decay of charmed particles into hadronic final states containing a pK^- or K^+K^- pair, particularly Λ_c^+ and D_s^+ . We used the ACCMOR spectrometer [9] with an improved vertex detector containing charge-coupled devices, CCDs [10], for the first time. A modified version of the FAMP trigger [11] was used to record a total of 17 million events containing a pair of opposite charge kaons and/or protons.

2. EXPERIMENTAL SETUP

The NA32 experiment was situated in the North Area of the CERN SPS and used an un-separated negative beam with a momentum of 230 GeV/c. Two CEDAR Cerenkov counters tagged incident pions (96%) and kaons (4%). The vertex detector consisted of a beam telescope of 7 silicon microstrip detectors (MSDs) and a vertex telescope of 2 CCDs and 8 MSDs. The CCDs, situated 1 cm and 2 cm in a vacuum downstream of a 2.5 mm thick Copper target, measured high precision space points (~ 5 μ m) on tracks close to the production vertex. Straight line tracks are reconstructed with a precision on their transverse position of approximately $[5^2 + (18/p)^2]^{\frac{1}{2}}$ μ m, where the momentum dependent term (p is in GeV/c) is due to

*) Unless explicitly stated, a particle symbol stands for particle and antiparticle.

multiple scattering. The high precision vertex detector and the lack of material for producing secondary interactions allow the clean reconstruction of charm decays with very few background events. The choice of a thin target (2.5 mm) was essential to enable the observation of charmed particles with very short lifetimes.

The large acceptance ACCMOR spectrometer consisted of two magnets and 48 planes of drift chambers [9]. Three multicellular threshold Cerenkov counters served to identify π, K, p in the momentum range 4 to 80 GeV/c. A two-level trigger was used to increase by a factor of 5 the sensitivity of the experiment to decays containing oppositely charged pairs of kaons and/or protons. The decay mode presented in this letter, $\Xi_c^0 \rightarrow pK^-\bar{K}^*0$, more than satisfies our trigger conditions. More details on the trigger are given in Ref. 9.

3. DATA ANALYSIS

The method used to search for decays is very similar to that applied in our Λ_c^+ analysis [2]. Briefly the data analysis consists of the following steps (more details may be found in Reference 2).

Firstly, all tracks are reconstructed separately in the beam and vertex telescopes and the drift chambers of the spectrometer and then the vertex telescope and drift chamber tracks are matched together. Particles are identified using the information from the Cerenkov detectors.

The next step is to search for vertices. The primary vertex is reconstructed from the beam track and as many of the outgoing tracks as possible. For those events where the primary vertex is found to be inside the copper target and where there are at least two tracks which do not originate from the primary vertex, a search is made for secondary vertices. Events are selected containing at least one secondary vertex outside of the copper (to remove secondary interactions). Strange particle decays (K^0, Λ^0) are removed. Approximately 300,000 events remain at this stage.

The secondary vertices are then scanned for fully reconstructed charm decays with no missing neutral particles, by restricting to those decays where the momentum vector sum of the decay products points back to the primary vertex (χ^2 probability greater than 1%). Invariant mass distributions consistent with the particle identification are then plotted. In our Λ_c^+ analysis [2], for example, the mass distribution for the $pK^-\pi^+$ channel contained a clear Λ_c^+ signal of 135 events above a background of 31. The background was mainly due to reflections from other charm particle decays where there was an ambiguity either in the topology of the decay or in the particle identification. The precise measurement of space points by our vertex detector allows the clean reconstruction of charm decays in a purely topological way with no restriction

to particular decay modes. Using this method we have observed rare decay modes which have not been previously seen [12].

The invariant mass distribution for the channel $pK^-K^-\pi^+$ is shown in Fig. 1a. We have removed those events with secondary vertices which are consistent with interactions in the CCDs and we have also demanded that all tracks have hits in at least one CCD. There are 33 decays passing the above cuts in the mass range 2.0 - 3.0 GeV/c². The bin with the largest content is that centred at 2475 MeV/c², suggesting that this may be evidence for a Ξ_c^0 signal, although at this stage there is a substantial background.

In the case of our Λ_c^+ analysis, further cuts were applied to the data, improving the ratio of signal to background by almost a factor 4. One of these was to demand that all three tracks were displaced from the primary vertex (3σ , 3σ and 1σ). As it is possible that the Ξ_c^0 has a very short lifetime, we were unable to use this approach here as this would have reduced our acceptance too much. However, other cuts could be used to purify the $pK^-K^-\pi^+$ sample, as follows :

- i) Reflections from other fully reconstructed charm events are removed (see Fig. 1b). The 7 decays which are cut are mainly due to $\Lambda_c^+ \rightarrow pK^-\pi^+$ or $D^0 \rightarrow K^+K^-\pi^+\pi^-$ where there is an additional pointing track superimposed in the first case and where the particle identification is ambiguous in both cases.
- ii) By studying the $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays we define a tighter particle identification algorithm for selecting "non-pions" (i.e. kaons and protons). Demanding two such non-pions per decay in the Λ_c^+ sample only reduces the number of accepted decays by 15%, but at the same time decreases the background by a factor of two. Many of the events in Fig. 1b contain particles which could be either kaons or pions according to our looser identification cuts. We therefore demand three non-pions in the $pK^-K^-\pi^+$ events thereby reducing the sample to 12 events (see Fig. 1c).
- iii) In our Ξ_c^+ analysis [5] we found that the three decays to $\Sigma^+K^-\pi^+$ were all consistent with the $K^-\pi^+$ originating from a $\bar{K}^*(892)^0$. Following this, we demand that one of the two $K^-\pi^+$ combinations have an effective mass within the range 796 to 996 MeV/c² (i.e. $\pm 2\Gamma$). Figure 1d shows the resulting distribution : four events cluster about a mass of approximately 2470 MeV/c² and there are only another three events, all above a mass of 2900 MeV/c².

Given the very clean signal with virtually no background, these four events are clear evidence for the decay mode $\Xi_c^0 \rightarrow pK^-\bar{K}^*(892)^0$. Three of the decays are Ξ_c^0 while the fourth one is a $\bar{\Xi}_c^0$. Two of the Ξ_c^0 and the $\bar{\Xi}_c^0$ are produced by incoming pions while the re-maining Ξ_c^0 is produced by an incoming K^- . In the latter case the Ξ_c^0 contains an s-quark, like the beam particle. More details of the decays are presented in Table 1.

4. RESULTS

The results presented here are based on the full data sample of 17 million triggers. The weighted mean mass of the four $\Xi_c^0 \rightarrow pK^-\bar{K}^{*0}$ decays is 2473.3 ± 1.9 MeV/c² in good agreement with the CLEO measurement of $2472 \pm 3 \pm 4$ MeV/c² [5,6]. As in the case of our Λ_c^+ analysis [2], we estimate the systematic uncertainty on the Ξ_c^0 mass to be ± 1.2 MeV/c². Combining this with the Ξ_c^+ mass of 2466.5 ± 2.7 MeV/c² from our earlier letter [5], we measure an isospin mass splitting of $M(\Xi_c^+) - M(\Xi_c^0) = -6.8 \pm 3.3$ MeV/c². The systematic error in this case is much smaller because of several effects which cancel out; we estimate it to be approximately ± 0.5 MeV/c². This result, taken together with that of CLEO, indicates that the Ξ_c^0 is heavier than the Ξ_c^+ , which puts a restriction on several theoretical predictions [see Reference 13 for an extensive discussion].

The mean uncorrected flighttime of the four Ξ_c^0 decays is $2.4 \cdot 10^{-13}$ s. To measure the Ξ_c^0 lifetime, we must correct the observed decay lengths for the acceptance of the cuts of our analysis. For each event, we determine the minimum detectable decay length $\ell_{\min}$ and calculate the corrected proper time $t = (\ell - \ell_{\min}) M(\Xi_c) / cP(\Xi_c)$, where ℓ and $P(\Xi_c)$ are the decay length and momentum of the Ξ_c^0 decay. The resulting mean Ξ_c^0 lifetime is $(0.82 \pm_{0.30}^{0.59}) \cdot 10^{-13}$ s. We have checked for possible sources of systematic error on the Ξ_c^0 lifetime. These include a non-constant geometrical acceptance as a function of decay position, distortion in the reconstruction of secondary vertices and a varying efficiency for finding vertices within the decay volume. In a similar way to our Λ_c^+ analysis [2], we find that the systematic error is negligible compared to the quoted statistical errors. This is the first measurement of the Ξ_c^0 lifetime and is the shortest charmed particle lifetime ever measured.

Two theoretical calculations of charmed baryon lifetimes have been published [14,15]. These are based on a spectator diagram, W-exchange and quark interference with QCD effects. Guberina et al. [14] predict $\tau(\Omega_c^0) \approx \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+)$, whereas Voloshin and Shifman [15] predict $\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) \approx \tau(\Xi_c^+)$, where each inequality represents a factor between 1.5 and 2.0. Our measurements of $\tau(\Xi_c^0)$, $\tau(\Xi_c^+) = (2.0 \pm_{0.8}^{1.1}) \cdot 10^{-13}$ s [5] and $\tau(\Lambda_c^+) = (1.96 \pm_{0.20}^{0.23}) \cdot 10^{-13}$ s [2] support the latter prediction, although more statistics is required to make a firm conclusion.

We have searched for resonant components in the Ξ_c^0 decays. There are two $K^-\pi^+$ combinations per decay. The presence of at least one $\bar{K}^*(892)^0$ was demanded in the extraction of the signal, but as may be seen in Table 1, events 2 and 4 have two $K^-\pi^+$ masses within $\pm 2\Gamma$ of the $\bar{K}^*$ mass. There are also two pK^- mass combinations per decay. For events 1 and 3, using the kaon which is not part of the $\bar{K}^*$ combination, the pK^- masses are found to be 1511 and 1525 MeV/c² respectively. For event 4, the pK^- masses corresponding to the $\bar{K}^*$ combinations are 1529 and 1545 MeV/c². These pK^- masses are compatible with the decay of the narrow

$\Lambda(1520)$ resonance, suggesting that the Ξ_c^0 might decay to $\Lambda(1520)\bar{K}^*(892)^0$. We cannot interpret these data as being conclusive evidence for $\Lambda(1520)$ because the available phase space tends to force the pK^- mass into the region of the $\Lambda(1520)$.

Before we can measure the total production cross-section of Ξ_c^0 by pions, we must determine the acceptance of the geometry of our experimental setup, the trigger and the cuts of the analysis. This is calculated in a Monte Carlo simulation of Ξ_c^0 production using the usual distribution $d^2\sigma/dx_F dp_t^2 \sim (1-x_F)^n e^{-bp_t^2}$ where x_F and p_t are the Feynman variable and transverse momentum of the Ξ_c^0 . We assume a similar production mechanism to that we have observed for Λ_c^+ [16], i.e. $n=3$ and $b=1 \text{ GeV}^{-2}$, and use the Ξ_c^0 lifetime as presented in this letter. The Ξ_c^0 are simulated together with D mesons (67% $\bar{D}^0$ and 33% D^-) and merged with additional tracks from real events. The acceptance for the channel $\Xi_c^0 \rightarrow pK^-\bar{K}^{*0}$ is found to be 1.1%, including allowance for the non-observed all neutral decay mode of the $\bar{K}^*(892)^0$.

Assuming a linear A-dependence, we measure from the three pion induced Ξ_c^0 events a Ξ_c^0 production cross-section times branching fraction of $\Xi_c^0 \rightarrow pK^-\bar{K}^*(892)^0$ to be $0.019 \pm 0.011 \pm_{0.009}^{0.066} \mu\text{b}$ per nucleon for $x_F > 0$. The first error is statistical, the second one systematic and reflects mainly the uncertainties on the Ξ_c^0 lifetime, on the value of n and on the trigger simulation (for n we assume an uncertainty of ± 2).

We have looked for the decay mode $\Xi_c^0 \rightarrow \Xi^-\pi^+$ as observed by CLEO [6]. Ξ^- particles are reconstructed via their decay into $\Lambda^0\pi^-$ as in our Ξ_c^+ analysis [5]. Selecting two-prong secondary vertices containing a Ξ^- and π^+ with both tracks displaced from the primary vertex results in 8 decays all of which have effective masses less than $2110 \text{ MeV}/c^2$. The decay of Ξ_c^0 to $\Xi^-\pi^+$ would be highly asymmetric in the laboratory frame making the Ξ^- travel forwards; relaxing the requirement that the Ξ^- be displaced from the primary vertex increases the number of selected events to 160 but all masses are less than $2170 \text{ MeV}/c^2$. We therefore do not observe $\Xi_c^0 \rightarrow \Xi^-\pi^+$.

We have reported here on the possible observation of the decay mode $\Xi_c^0 \rightarrow \Lambda(1520)\bar{K}^{*0}$. In addition to decaying to $N K$ the $\Lambda(1520)$ also decays to $\Sigma\pi$. We have therefore searched for the decay mode $\Xi_c^0 \rightarrow \Sigma^+\pi^-K^-\pi^+$. Using very similar techniques to our analysis of $\Xi_c^+ \rightarrow \Sigma^+K^-\pi^+$ [5] we found no events in this channel. Given the fact that we are only able to reconstruct Σ^+ , and not Σ^0 or Σ^- , and then only via its decay to $p\pi^0$ means that the three possible Ξ_c^0 decays to $\Lambda(1520)\bar{K}^*$ lead us to expect to see approximately one decay via $\Sigma^+\pi^-K^-\pi^+$, fully consistent with our null result in this channel.

5. CONCLUSIONS

We have observed four unambiguous decays of $\Xi_c^0 \rightarrow pK^-\bar{K}^*(892)^0$. We measure the mass of Ξ_c^0 to be $2473.3 \pm 1.9 \pm 1.2$ MeV/c² and the isospin mass splitting $M(\Xi_c^+) - M(\Xi_c^0)$ to be $-6.8 \pm 3.3 \pm 0.5$ MeV/c². We have measured the Ξ_c^0 lifetime for the first time and find it to be $(0.82 \pm_{0.30}^{0.59}) \cdot 10^{-13}$ s. Assuming a similar production mechanism of Ξ_c^0 by pions as for Λ_c^+ , we determine the Ξ_c^0 production cross-section times branching fraction of $\Xi_c^0 \rightarrow pK^-\bar{K}^*(892)^0$ to be $0.019 \pm 0.011 \pm_{0.009}^{0.066} \mu\text{b}$ for $x_F > 0$. Three of the decays are consistent with the pK^- being decay products of the $\Lambda(1520)$ resonance.

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Table 1

Details of the four $\Xi_c^0 \rightarrow pK^-K^-\pi^+$ decays

Event	1		2		3		4	
Mass of (pKK π) system (MeV/c ²)	2470.5 $\pm$ 3.7		2476.6 $\pm$ 4.0		2478.1 $\pm$ 4.0		2470.0 $\pm$ 3.3	
Total momentum (GeV/c)	123.1		56.6		129.2		65.8	
Distance of total momentum vector to primary vertex and its error (μ m)	6.5 (4.4)		3.6 (3.8)		3.8 (4.5)		1.9 (3.5)	
Distance of decay vertex to target edge (standard deviations)	5.2		3.0		19		1.1	
Mass of (K $^-\pi^+$) system 2 solutions (MeV/c ²)	868	780	830	932	865	791	848	849
Mass of associated (pK $^-$) systems (MeV/c ²)	1511	1491	1561	1435	1525	1674	1529	1545
Decay length ℓ (mm)	2.47		2.14		4.42		1.62	
$\ell_{\min}$ (mm)	1.43		1.68		1.83		1.41	
Corrected lifetime (10 ⁻¹³ s)	0.70		0.67		1.65		0.26	
Reaction	$\pi^- \rightarrow \Xi_c^0$		$\pi^- \rightarrow \Xi_c^0$		$\pi^- \rightarrow \Xi_c^0$		$K^- \rightarrow \Xi_c^0$	

Figure Captions

Fig. 1 Invariant mass distribution of the $pK^-K^-\pi^+$ channel :

- a) After standard cuts (≥ 2 displaced tracks)
- b) After removal of reflections.
- c) After tightening particle identification.
- d) After demanding $\bar{K}^{*0} \rightarrow K^-\pi^+$.

Fig. 1