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MEASUREMENT OF THE MASS AND LIFETIME OF THE CHARMED STRANGE BARYON Ξ_c^+ IN TWO NEW DECAY MODES

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ABSTRACT

We have observed five unambiguous decays of the charmed strange baryon Ξ_c^+ in the collision of 230 GeV/c negative pions on a copper target at the CERN SPS using silicon microstrip detectors and charge-coupled devices for vertex reconstruction. Three of them have been reconstructed through the decay chain $\Xi_c^+ \to \Xi^-\pi^+\pi^+$, $\Xi^- \to \Lambda^0\pi^-$, $\Lambda^0 \to p\pi^-$ (or charge conjugate) and the other two through the decay chain $\Xi_c^+ \to \Sigma^+K^-\pi^+$, $\Sigma^+ \to p\pi^0$ (or charge conjugate). We present our measurements of the mass and lifetime of the Ξ_c^+ and also give preliminary determinations of the production cross-section and relative branching fractions.

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1. INTRODUCTION

Except for the Λ_c^+ there is little experimental information on the four weakly-decaying singly-charmed baryons expected theoretically : Λ_c^+(cud), Ξ_c^+(csu), Ξ_c^0(csd) and Ω_c^0(css). The Ξ_c^+ has been observed by the CERN hyperon beam experiment in the reaction Σ^-(135 GeV/c)+Be $\rightarrow \Lambda^0 K^- \pi^+ \pi^+$+X [1] and by an experiment at FNAL in the reaction n(~600 GeV/c)+W/Si/Be $\rightarrow \Lambda^0$(or Σ^0)$K^- \pi^+ \pi^+$+X [2], with an average mass of 2460±19 MeV/c^2 [3]. There appears to be a discrepancy between the two experiments as the second one sees two peaks in the $\Lambda^0 K^- \pi^+ \pi^+$ mass spectrum, while the first one only sees one peak. The Ξ_c^0 has been recently observed by the CLEO Collaboration in the decay mode $\Xi^- \pi^+$ at a mass of 2471±3±4 MeV/c^2 [4]. The Ω_c^0 has been observed by the CERN hyperon beam experiment through three decays in the decay mode $\Xi^- K^- \pi^+ \pi^+$ whose masses cluster around 2740 MeV/c^2 [1].

For rare decays a precise reconstruction of decay vertices is not enough to suppress the background. One also needs an unambiguous particle identification that Cerenkov counters do not always provide. The baryon character of a charmed baryon can be better ascertained in decays involving $\Sigma^\pm$ or Ξ^- hyperons through a clean reconstruction of their subsequent decay. Decays involving a Λ^0 suffer more from combinatorial background because the Λ^0 track cannot be seen in the vertex detector and it is generally impossible to decide which vertex the Λ^0 is coming from. We have therefore concentrated our studies of charmed strange baryons on decay modes like $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ or $\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+$.

Our experiment was performed in 1985-1986 at the CERN SPS. Its main aim was the study of production and decay properties of charmed particles produced in hadronic collisions and decaying hadronically into final states containing a pair of opposite charge kaons and/or protons. It was a continuation of the NA32 experiment [5] using the ACCMOR spectrometer, an improved vertex detector and a dedicated trigger. For the first time charge-coupled devices, CCDs [6], were used as vertex detectors. They provide high precision (~ 5 μm) space points on tracks close to the target. A modified version of the FAMP trigger [7] was used to trigger on events containing a pair of opposite charge kaons and/or protons. A total of 16.7 million triggers have been recorded.

2. THE EXPERIMENT

A negative beam with a momentum of 230 GeV/c was used. Two CEDAR Cerenkov counters served for tagging incident pions and kaons (96% and 4% respectively).

Hadronic charm decays into charged particles were fully reconstructed with the vertex detector and the large acceptance spectrometer [8] shown in Fig. 1. The vertex detector consisted of two parts - a beam telescope with 7 silicon microstrip detectors (MSDs) and a vertex telescope with 2 CCDs at 10 and 20 mm behind the target and 8 MSDs positioned from 65 to 180 mm behind the target. A short 2.5 mm Cu target was used so that decay vertices could be observed in vacuum close to the primary vertex. The spectrometer consisted of 2 magnets M1 and M2 and 48 planes of drift chambers arranged in 4 groups, DC_1 to DC_4. Three multicellular threshold Cerenkov counters, C_1 to C_3, were used to identify π,K,p in the momentum range 4-80 GeV/c.

The trigger had two levels, a hardware trigger and the FAMP trigger. They are described in Ref. [8]. Compared to a simple interaction trigger, this two-level trigger increased by a factor 5 the sensitivity of the experiment for decays with a pair of opposite charge K/p in the final state.

While decays like $X \to \Sigma^+K^-\pi^+(\Sigma^+\to p\pi^0)$ satisfy the trigger conditions by themselves, decays like $X \to \Xi^-\pi^+\pi^+$ ($\Xi^- \to \Lambda^0\pi^-$, $\Lambda^0 \to p\pi^-$) do not*). However the kaon from the decay of the associated charmed partner or accompanying pions, simulating kaons or protons, permit such reactions to fulfil the trigger conditions with a sizeable, though reduced, efficiency. Through this mechanism we have obtained substantial samples of $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$ or $K^-\pi^+\pi^+\pi^-$ in this experiment [9].

3. RECONSTRUCTION OF Ξ HYPERONS

We look for the cascade $\Xi^- \to \Lambda^0\pi^-$, $\Lambda^0 \to p\pi^-$ and, at the same time, $\Omega^- \to \Lambda^0K^-$, $\Lambda^0 \to p\pi^-$. In order to achieve a strong rejection of background, one has to reconstruct the mother track and the three charged decay tracks, measure their momenta and identify them. On the other hand one would like to keep the acceptance as large as possible. We restricted the search for Ξ/Ω to decays in front of the onset of the magnetic field in M1 (70 cm downstream of the target) so that one avoids complications with the bending of the Ξ/Ω track in M1 (Fig. 2). We also restricted the search to decays beyond CCD_2 so that the Ξ/Ω track can always be reconstructed in the vertex detector. For convenience we split the search procedure into three parts corresponding to different intervals of the accepted Ξ decay range (Fig. 2). The asymmetric decay of the Ξ and of the Λ^0 frequently prevents either decay pion to reach DC_2. A reasonable compromise between background rejection and larger acceptance was to restrict the search to Λ^0 decays in front of DC_1 (285 cm downstream of the target) and to require the π/K from Ξ/Ω decay and the pion from Λ^0 decay to be detected in DC1. As a consequence i) the momentum of the π/K can always be measured, ii) the momentum of the pion from Λ^0 decay can be measured for most Λ^0 decays. The forward-going proton from Λ^0 decay

*) Unless explicitly stated, particle symbols will be used throughout to denote particles and antiparticles.

is required to be detected in DC_1 and DC_2 so that its momentum can always be determined from its deflection in M2. Under these conditions the background was found to be small and it was decided not to require particle identification in order not to decrease unnecessarily the acceptance.

As explained before, the Ξ/Ω can decay anywhere between CCD_2 and M1, thereby being seen in a variable number of MSD planes (0 to 8, and reciprocally for the π/K from its decay). As one can see in Figure 2, the reconstruction of the Ξ/Ω decay vertex is rather straightforward for decays in the vertex detector because it has to be at the intersection of two precisely reconstructed tracks. It is not so for the third range and we will give a description of the full Ξ/Ω search in this case. First events are selected which contain at least one track seen in the vertex detector but not in the drift chambers ("Ξ/Ω" tracks). The search for Ξ/Ω decay is made by iterating along the "Ξ/Ω" tracks between MSD_8 and the onset of the magnetic field in M1. For each iterative point on a "Ξ/Ω" track a good match is looked for with a track in the drift chambers, assumed to correspond to the meson from Ξ/Ω decay, and a search is made for a V^0 whose decay products are seen in DC_1, compatible with being produced from that point. All three tracks, i.e. meson from Ξ/Ω decay, p and π^- from Λ^0 decay, should not be seen in the vertex telescope. As we do not use particle identification, any V^0 can be interpreted as $p\pi^-$, $\pi^+\bar{p}$ or $\pi^+\pi^-$. The invariant mass of either of the first two interpretations is required to be within 20 MeV/c^2 of the Λ^0 mass. In addition, the "Ξ/Ω" track should have an angle of less than about 2 mr with the sum of the momentum vectors of the meson from the Ξ/Ω decay and of the Λ^0. Once a good cascade is found, its reconstruction is further refined using smaller iteration steps and the Ξ/Ω decay vertex is taken to be the point which corresponds to the minimum of the sum of the χ^2 for the meson from Ξ/Ω decay to originate from it and of the χ^2 for the Λ^0 to be produced from the same point.

As we do not use particle identification, each cascade can be interpreted either as a $\Xi^- \rightarrow \Lambda^0\pi^-$ candidate or as a $\Omega^- \rightarrow \Lambda^0 K^-$ one. The small fraction of ambiguities is removed by requiring $|Mass_{K^-\Lambda^0} - Mass_{\Omega^-}| > 15$ MeV/c^2 for the Ξ candidates and $Mass_{\pi^-\Lambda^0} > Mass_{\Xi^-} + 15$ MeV/c^2 for the Ω ones. Figures 3 and 4 show the distribution of $Mass_{\pi^-\Lambda^0}$ and $Mass_{K^-\Lambda^0}$ for the 2 samples respectively as obtained from all the 16.7 million triggers. Clean Ξ and Ω mass peaks are observed over a small background. They contain approximately 7500 Ξ^-, 5700 $\overline{\Xi}^+$, 720 Ω^- and 580 $\overline{\Omega}^+$. The tails of the $\pi^-\Lambda^0$ mass distribution reflect some distortion induced by the reconstruction procedure for the third range of the Ξ decay, in particular when the Λ^0 decays closely behind the Ξ. This effect is not seen in the $K^-\Lambda^0$ mass distribution where the more symmetric decay of the Ω allows a more precise reconstruction of its decay vertex.

4. THE DECAY MODE $\Xi_c^+ \to \Xi^-\pi^+\pi^+$

The analysis is similar to the one used for our Λ_c^+, D_s^+, D^+ and D^0 studies [9]. We first look for decay vertices, having a χ^2 probability of better than 1% between the track of a reconstructed Ξ^- and two other π^+ tracks. Then we require 1) the effective mass of the $\Lambda^0\pi^-$ system to be within ± 25 MeV/c^2 of the Ξ mass, 2) all three tracks in a decay vertex to be incompatible with originating from the primary vertex, with a χ^2 probability less than 1% - so as to exclude topological ambiguities, 3) the decay vertex to be outside the target, so as to exclude secondary interactions, 4) the total momentum sum of the decay vertex to be compatible with passing through the primary vertex with a χ^2 probability better than 1%.

Under these conditions three events were selected out of the total sample of 16.7 million triggers. The second requirement, stronger than the one used in Ref.[9], turned out to be very powerful in suppressing the background. Table 1 gives the characteristics of the three events. One sees that their $\Xi\pi\pi$ effective masses cluster around 2465 MeV/c^2. Our Λ_c^+ studies already showed that the precision of the vertex detector allows the selection of clean decay vertices in vacuum and we find a background of only 7% under the mass peak in the decay mode $\Lambda_c^+ \to pK^-\pi$. Here in the $\Xi\pi\pi$ decay mode the presence of a Ξ in the final state gives an additional signature which reduces the background level further down. As a cross check, using the same selection criteria, we also looked for $\Xi\pi\pi$ decay vertices where the two pions have opposite charges and where no charmed particles are expected. No event was selected.

We therefore interpret the three events as evidence for a new, Cabibbo-favoured, decay mode of the Ξ_c^+ (csu) baryon . All three Ξ_c events have been produced by incident pions. One decay is a Ξ_c^+, the other two are $\bar{\Xi}_c^-$, whereas only Ξ_c^+ have been observed in Refs.[1] and [2].

Taking the Ξ^- mass to be 1321.32 MeV/c^2 [3] we find a weighted mean mass $M_{\Xi_c^+}$ = 2465.4±4.0 MeV/c^2 in good agreement with the previous determination 2460±19 MeV/c^2 [3]. We have studied the effect of the systematic uncertainties of the geometry and of the magnetic fields of our spectrometer on the absolute mass scale. After checking it with samples of K_S^0, Λ^0, D^0, D^+, D_s^+ and Λ_c^+ we estimate a systematic uncertainty of 1.5 MeV/c^2 on the Ξ_c^+ mass.

5. RECONSTRUCTION OF Σ^+ HYPERONS

The Σ^+ hyperon decays almost equally into $p\pi^0$ and into $n\pi^+$. The Σ^- hyperon decays exclusively into $n\pi^-$. In order to achieve a strong rejection of the background we required a baryon to be identified in the decay products. Since our set-up was not detecting neutral particles, we restricted the search to decays of Σ^+ into $p\pi^0$. For momenta larger than 13 GeV/c, more than 50% Σ^+ decay between the last plane of the vertex detector and the first plane of the drift chamber group DC_1. In addition the proton from Σ^+ decay is emitted forward, with an angle with respect to the Σ^+ direction which has to be less than the kinematical limit θ_{max} = 189/p mr, where p is the proton momentum in GeV/c. It can therefore be detected in DC_1 and DC_2 to DC_4 and in the Cerenkov counters C_1 to C_3, so that its momentum can be determined from its deflection in M2 and that it can be identified.

In these circumstances a Σ^+ decay can be recognized as a kink between a track reconstructed in the vertex detector but not in the drift chambers ("Σ" track) and a track reconstructed in DC_1 and DC_2 to DC_4 and identified by the Cerenkov counters as being that of a proton ("proton" track). The position of a "proton" track in the interval MSD_8 - DC_1 is measured with a precision of about 1 mm and its direction with a precision of about 0.4 mr. The position and the direction of a "Σ" track are measured more precisely. Therefore a Σ^+ decay can be recognized if a "Σ" track and a "proton" track are found which pass each other within about 2.5 mm in the interval MSD_8 - DC_1 and which have an angle larger than about 1 mr and less than θ_{max}. Once a Σ^+ decay is recognized in this way, the Σ^+ momentum can be determined from the proton momentum and from the kink angle with the well-known twofold ambiguity. Some complications arise if the Σ^+ decays inside the magnetic field of M1, due to the bending of both Σ^+ and proton tracks. We will come back to this problem in the next section.

The strength of this procedure together with the cleanliness of the reconstruction of decay vertices in the vertex detector has been demonstrated in this experiment by the observation of 11 decays $\Lambda_c^+ \to \Sigma^+\pi^+\pi^-$ [9].

6. THE DECAY MODE $\Xi_c^+ \to \Sigma^+K^-\pi^+$

The analysis is very similar to the one described in section 4. We first look for decay vertices, having a χ^2 probability of better that 1%, between the track of a reconstructed Σ^+ and two other tracks, identified as K^- and π^+ respectively. Then we imposed the conditions 2, 3 and 4 specified in section 4.

Under these conditions five events were selected out of the total sample. Three decays have a "kaon" whose identification is ambiguous with that for a pion. They can therefore be interpreted as $\Sigma^+\pi^-\pi^+$ and all three have one of the two possible solutions for the $\Sigma\pi\pi$ effective mass compatible with the Λ_c^+ mass. One of them also offers a solution for the $\Sigma K\pi$ effective mass compatible with our determination of the Ξ_c^+ mass. The remaining two events have no K/π ambiguity and have a $\Sigma K\pi$ mass solution compatible with the Ξ_c^+ mass. Table 2 gives their characteristics. In order to further investigate the background we also looked for decay vertices with other charge states, namely $\Sigma^+K^+\pi^-$ and $\Sigma^+K^-\pi^-$. Using the same selection criteria five events were selected. All but one suffer from K/π ambiguity. Four are interpreted as Λ_c^+ decays. There is no conclusive interpretation for the fifth one.

Considering the low level of unexplained background (one event in 10) together with the larger abundance of Λ_c^+ decays, we only retain the two events of Table 2 and interpret them as evidence for another new, Cabibbo-favoured, decay mode of the Ξ_c^+. The two events have been produced by incident pions. The first decay is a Ξ_c^+, the other one a $\bar{\Xi}_c^-$. The second event appears as a remarkable instance of hadronic production of a pair of charmed baryon and charmed strange antibaryon, whose decays are fully reconstructed :

$$\pi^- + Cu \rightarrow X^- + \bar{\Xi}_c^- + \Lambda_c^+ + neutrals,$$

$$\bar{\Xi}_c^- \rightarrow \bar{\Sigma}^- K^+ \pi^- \ (mass = 2475 \pm 15 \ MeV/c^2),$$

$$\Lambda_c^+ \rightarrow p K^- \pi^+ \ (mass = 2284.3 \pm 5.0 \ MeV/c^2).$$

As mentioned in the previous section, the reconstruction of a Σ^+ decay suffers from complications when the decay occurs inside the magnetic field of M1. The smallness of the angle between the Σ^+ track and the proton track results in a poor precision on the measurement of the longitudinal position of the decay. In some cases it is impossible to decide whether the decay occurred outside or inside the magnetic field and to make due corrections to the kinematics for the bending off both Σ^+ and proton tracks in the magnetic field of M1. We are still investigating this problem. As a consequence the determination of the effective mass and of the associated error for the two decays $\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+$ reported in Table 2 should be considered as preliminary. We also prefer not to combine them with the mass measurement from the three decays $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$.

7. RESULTS

To measure the Ξ_c^+ lifetime, we have to correct for the acceptance of the selection criteria [10]. For each event with a decay length ℓ, we determine the minimum detectable decay length ℓ_{min} and calculate the corrected proper time $\Delta t = (\ell - \ell_{min})\ M_{\Xi_c}/cp_{\Xi_c}$. We have also made a global correction to account for the loss of events decaying after CCD_2. For the three $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ events, we obtain a mean lifetime $\tau = (5.1^{+4.6}_{-2.1}) \cdot 10^{-13}$s whereas for the two $\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+$ events, we obtain $\tau = (0.9^{+1.1}_{-0.4}) \cdot 10^{-13}$s. Since similar techniques and selection criteria are used in the analysis of the two decay modes, we combine the two measurements. The average lifetime of the five events is $\tau = (3.4^{+2.1}_{-1.2}) \cdot 10^{-13}$s in good agreement with the previous measurement of $(4.3^{+1.7}_{-1.2}) \cdot 10^{-13}$s [3].

There are two calculations of the lifetimes of the four charmed baryons (Λ_c^+, Ξ_c^+, Ξ_c^0 and Ω_c^0) based on a spectator diagram, W-exchange and quark interference with QCD effects [11,12]. While the first process leads to equal lifetimes, the W-exchange between c and d quarks shortens the lifetime of Λ_c^+ and Ξ_c^0. The constructive interference between the s quark from the $c \rightarrow su\bar{d}$ decay and the s quark in the initial state shortens the lifetimes of Ξ_c^+,

Ξ_c^0 and even more that of Ω_c^0 while the destructive interference lengthens the lifetimes of those with a u quark. As a result one obtains $\tau(\Omega_c^0) \leq \tau(\Xi_c^0) < \tau(\Xi_c^+)$. There is a controversy concerning the lifetimes of Ξ_c^+ and Λ_c^+. Guberina et al.[11] expect $\tau(\Xi_c^+) > \tau(\Lambda_c^+)$; using the non-relativistic quark model they obtain $\tau(\Xi_c^+) = 3.7 \cdot 10^{-13}$s and $\tau(\Lambda_c^+) = 2.3 \cdot 10^{-13}$s which is close to our results (the relativistic bag model yields $4.4 \cdot 10^{-13}$s and $3.7 \cdot 10^{-13}$s respectively; in both cases the absolute predictions are valid within a factor of 1.5-2.0). On the other hand, Volishin and Shifman [12] predict $\tau(\Lambda_c^+) = \tau(\Xi_c^+) \approx \frac{1}{2}\tau(D_0)$ and claim [13] that the difference may be attributed to overlooking of some terms ("hybrid logarithms") by Guberina et al.

Our result of $\tau(\Xi_c^+) = (3.4^{+2.1}_{-1.2}) \cdot 10^{-13}$s taken together with results of previous experiments indicates that $\tau(\Xi_c^+) > \tau(\Lambda_c^+) = (1.96^{+0.23}_{-0.20}) \cdot 10^{-13}$s [14].

We have looked for possible final state resonances in the Ξ_c^+ decay. For the 6 $\Xi^-\pi^+$ combinations in $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$ decays, we find the following effective masses : (1963,1887), (1965,1912), (1928,1939) MeV/c^2. These values are definitely incompatible with $\Xi(1530)^0$. For the mass of the $K^-\pi^+$ system in the two $\Xi_c^+ \rightarrow \Sigma^+K^-\pi^+$ decays, we find 936 and 908 MeV/c^2 respectively which can be interpreted as $K^*(892)$. There are theoretical suggestions that charmed baryons decay significantly into two-body and quasi-two-body final states [15]. Using a quark model calculation, Körner et al. have given detailed predictions for decay rates of charmed baryons to various two-body and quasi-two-body final states, in particular the partial widths for $\Xi_c^+ \rightarrow \Xi(1530)^0\pi^+$ to vanish and for $\Xi_c^+ \rightarrow \Sigma^+\overline{K}^{*0}$ to be large. These predictions seem to agree with our results.

We have determined the acceptance for the various decay modes of Ξ_c^+ with a Monte Carlo calculation assuming $(1-x_F)^n \exp(-bp_T^2)$ distribution with n = 3 and b = 1 GeV^{-2}, similar to what we have observed in Λ_c^+ production [16]. The lifetime of the Ξ_c^+ was taken to be $(4.3^{+1.7}_{-1.2}) \cdot 10^{-13}$s [3]. The Monte Carlo program includes the geometrical acceptance, the trigger simulation and the simulation of the offline selection [16]. The total acceptance of $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$ ($\Xi^- \rightarrow \Lambda^0\pi^-$, $\Lambda^0 \rightarrow p\pi^-$) decay was found to be 0.94±0.04%. From this and assuming linear A dependence, we deduce the product of production cross-section times branching fraction of $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$ to be 0.04±0.02±0.02 μb/nucleon for $x_F > 0.0$, where the first error is statistical and the second one is systematic. The systematic error comes mainly from the uncertainties in the lifetime, the values of n and b and the trigger simulation. Varying the Ξ_c^+ lifetime within the quoted error changes the acceptance by about $\pm^{20}_{30}$%, while varying the value of n or b by 20% changes the acceptance by 10%. In the Monte Carlo program we have assumed that the Ξ_c^+ is produced in conjunction with a mixture of 66.7% $\overline{D}^0$ and 33.3% D^- (since the D^0 cross-section is about a factor 2 higher than the D^+ cross-section [16]) and the latest D^0 and D^+ branching fractions as measured by Mark III are used [17]. Typically in 45% of the accepted events, a kaon is present in the decay of the associated $\overline{D}$ and 25% of these kaons are found as triggering particles. By varying the branching fraction of $\overline{D} \rightarrow K^+ + X$ from 0 to 100%, the total acceptance for $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ changes by ±12%. This shows that the acceptance is not very sensitive to the presence of a kaon from the decay of the charmed partner.

The acceptance for $\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+$ ($\Sigma^+ \rightarrow p\pi^0$) decay relative to the one for $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ ($\Xi^- \rightarrow \Lambda^0 \pi^-$, $\Lambda^0 \rightarrow p\pi^-$) was found to be $5.0^{+1.4}_{-0.7}$, where the error reflects mainly the uncertainties on the lifetime and on the production characteristics of Ξ_c^+. We obtained

$$\frac{B(\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+)}{B(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)} = 0.17 \pm^{0.24}_{0.11} \pm^{0.03}_{0.04}$$

We are still developing refinements to the Monte Carlo simulation program and the above results should be taken as preliminary.

8. CONCLUSION

By virtue of the precision of our vertex detector and of the unique signature of a Ξ^- or Σ^+ in the set-up, we have observed three background-free events in the reaction $\pi^- + Cu \rightarrow \Xi^- \pi^+ \pi^+ + X$ and two events in the reaction $\pi^- + Cu \rightarrow \Sigma^+ K^- \pi^+ + X$ that we interpret as evidence for two new decay modes of the charmed strange baryon Ξ_c^+. From the three $\Xi^- \pi^+ \pi^+$ decays we determine a mass $M_{\Xi_c^+} = 2465.4 \pm 4.0 \pm 1.5$ MeV/c^2. We also measure from all five decays a mean lifetime $\tau(\Xi_c^+) = (3.4^{+2.1}_{-1.2}) \cdot 10^{-13}$s, in agreement with the results of two previous experiments. Parametrizing the production cross-section by $(1-x_F)^3 e^{-1.0 p_T^2}$ and assuming a linear A dependence, we determine the product of production cross-section times branching fraction $B(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)$ to be $0.04 \pm 0.02 \pm 0.02$ µb per nucleon for $x_F > 0$. We also measure the relative branching fraction $B(\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+)/B(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)$ to be $0.17^{+0.24}_{-0.11}{}^{+0.03}_{-0.04}$.

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Table 1

Summary of properties of the three $\Xi^-\pi^+\pi^+$ decays

Event	1	2	3
Mass of ($p\pi$) from Λ^0 (MeV/c^2)	1132	1115	1109
Mass of ($\Lambda^0\pi$) from Ξ^- (MeV/c^2)	1302	1320	1323
Impact parameter of Ξ^- and its error (μm)	47 (10)	56 (7)	216 (10)
Impact parameter of first pion and its error (μm)	91 (7)	67 (25)	279 (9)
Impact parameter of second pion and its error (μm)	58 (7)	59 (17)	191 (10)
Mass of ($\Xi\pi\pi$) system (MeV/c^2)	2461.0±8.8	2462.5±7.0	2468.5±5.2
Total momentum (GeV/c)	34.2	58.1	83.2
Impact parameter of momentum sum and its error (μm)	9.1 (5.7)	5.2 (10.7)	9.6 (6.8)
Distance of decay vertex from target edge (standard deviations)	10	6	52
Decay length l (mm)	1.61	3.13	13.5
l_{min} (mm)	0.90	2.02	1.71
Corrected lifetime (10^{-13}s)	1.71	1.57	11.63

Table 2

Summary of properties of the two $\Sigma^+K^-\pi^+$ decays

Event	1	2
Angle (Σ,p) in mr	7.7	7.1
Momentum of proton (GeV/c)	16.7	24.2
Impact parameter of Σ and its error (μm)	69 (7)	34 (10)
Impact parameter of K and its error (μm)	103 (7)	74 (7)
Impact parameter of π and its error (μm)	18 (7)	250 (14)
Mass of ($\Sigma K \pi$) system 2 solutions (MeV/c^2)	2468±5 2453±5	2475±15 2393±15
Total momentum for first solution (GeV/c)	47.3	46.3
Impact parameter of momentum sum and its error (μm)	5.6 (4.7)	5.1 (8.3)
Distance of decay vertex from target edge (standard deviations)	2.5	23
Decay length l (mm)	2.78	1.98
l_{min} (mm)	2.50	1.28
Corrected lifetime (10^{-13}s)	0.49	1.23

Figure Captions

Fig. 1 Schematic view of the ACCMOR spectrometer with the details of the vertex detector in the inset. B1-B7 : silicon microstrip detectors for beam track reconstruction; T : 2.5 mm Cu target; CCDs : charge-coupled devices; I : interaction counter; MSD1-MSD8 : silicon microstrip detectors used together with CCDs for reconstruction of tracks and vertices (underneath are shown strip orientations with respect to horizontal plane).

Fig. 2 Sketch of Ξ/Ω reconstruction in the three decay ranges. Scale of vertex detector has been expanded as well as transverse scale with respect to longitudinal one.

Fig. 3 Invariant mass distribution of the $\Lambda^0\pi^-$ system for the $\Xi/\overline{\Xi}$ sample.

Fig. 4 Invariant mass distribution of the Λ^0K^- system for the $\Omega/\overline{\Omega}$ sample.

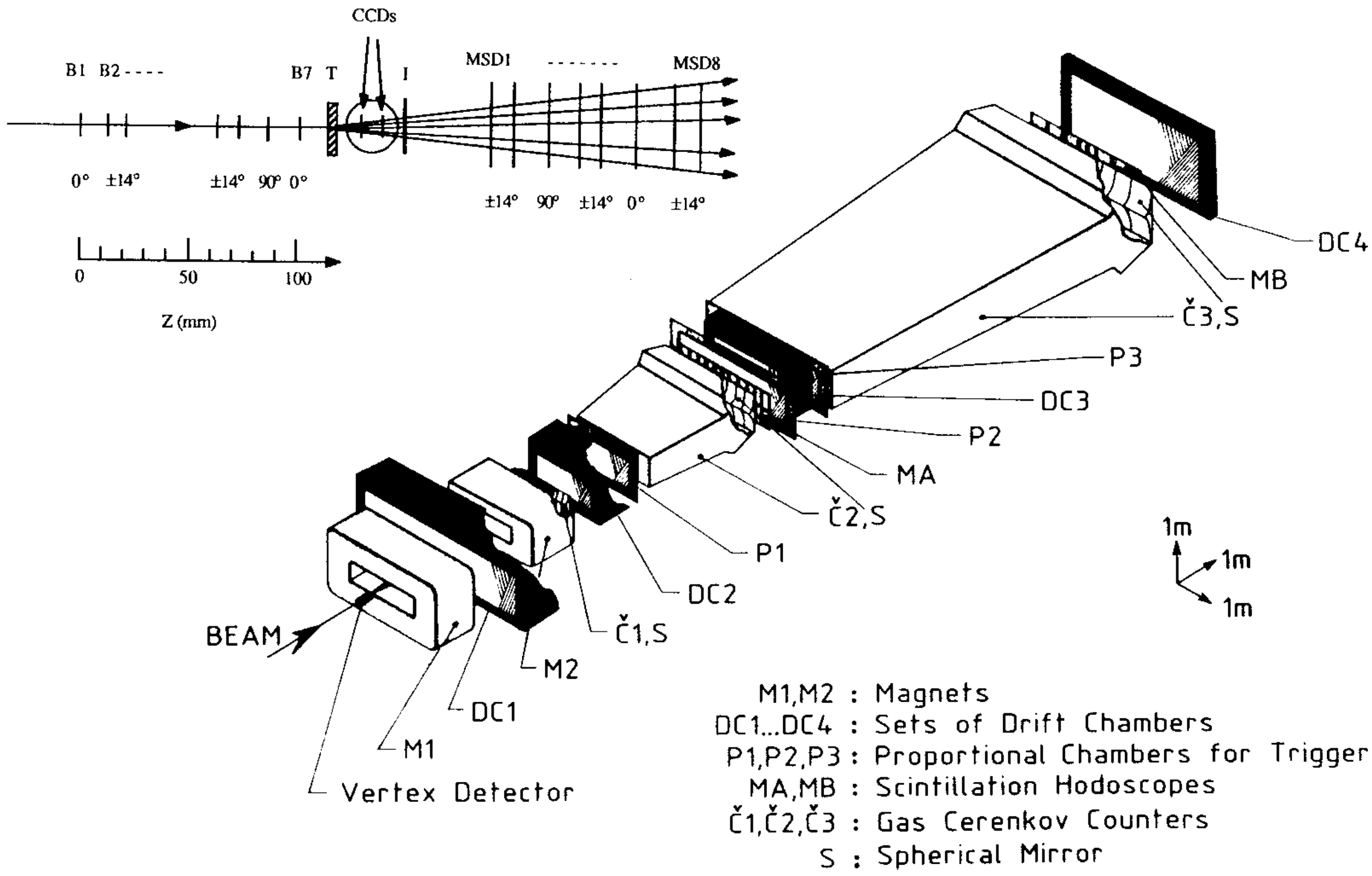

CCDs
B1 B2 ----
B7 T
I
MSD1 ------- MSD8
0° ±14° ±14° 90° 0°
±14° 90° ±14° 0° ±14°
0 50 100
Z (mm)
DC4
MB
Č3,S
P3
DC3
P2
MA
Č2,S
P1
DC2
Č1,S
M2
DC1
M1
Vertex Detector
BEAM
1m
1m
1m
M1,M2 : Magnets
DC1...DC4 : Sets of Drift Chambers
P1,P2,P3 : Proportional Chambers for Trigger
MA,MB : Scintillation Hodoscopes
Č1,Č2,Č3 : Gas Cerenkov Counters
S : Spherical Mirror

Fig. 1

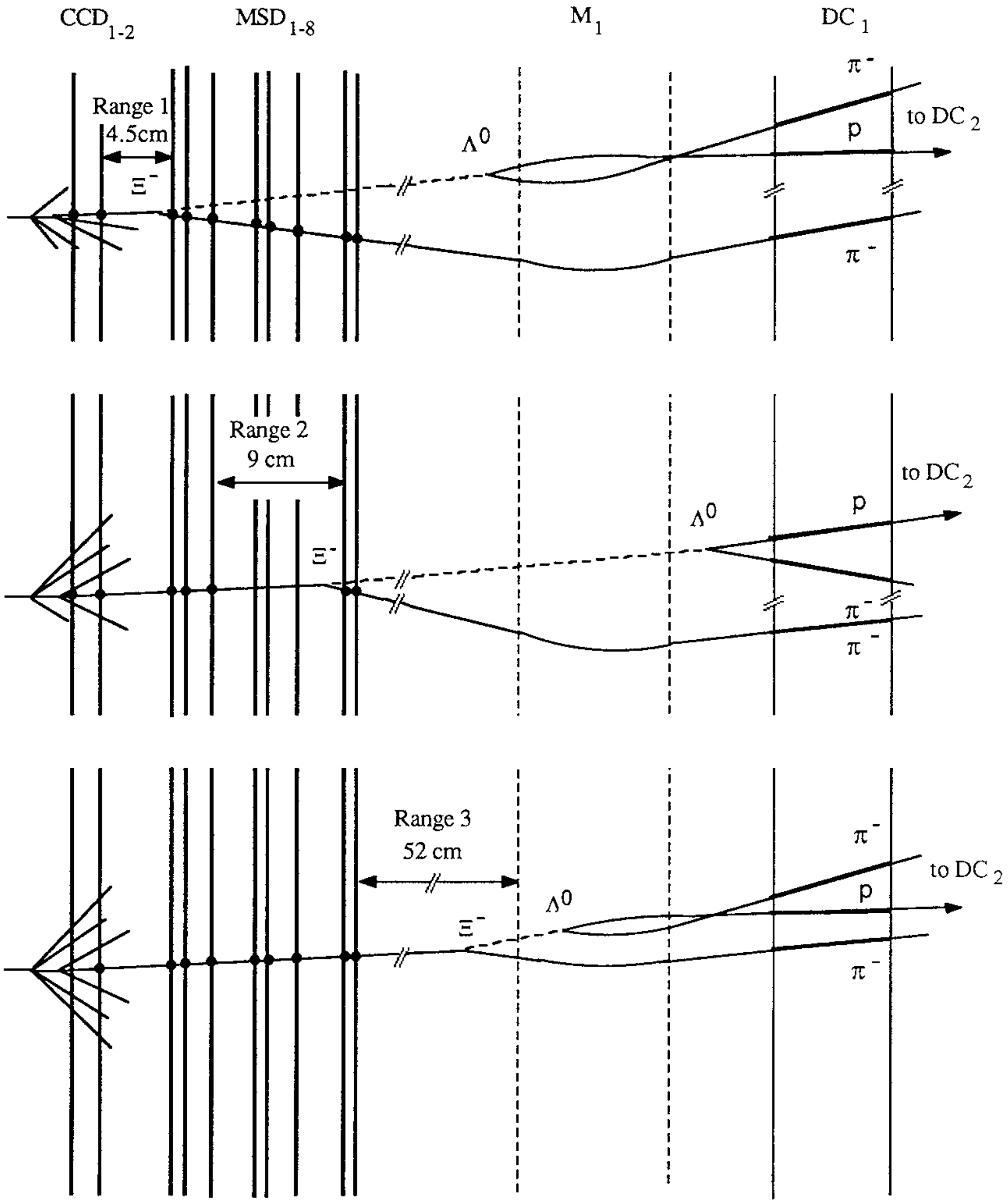

CCD 1-2
MSD 1-8
M 1
DC 1
Range 1
4.5cm
Ξ⁻
Λ⁰
π⁻
p
to DC 2
π⁻
Range 2
9 cm
Ξ⁻
Λ⁰
to DC 2
p
π⁻
π⁻
Range 3
52 cm
Ξ⁻
Λ⁰
π⁻
to DC 2
p
π⁻

Fig. 2

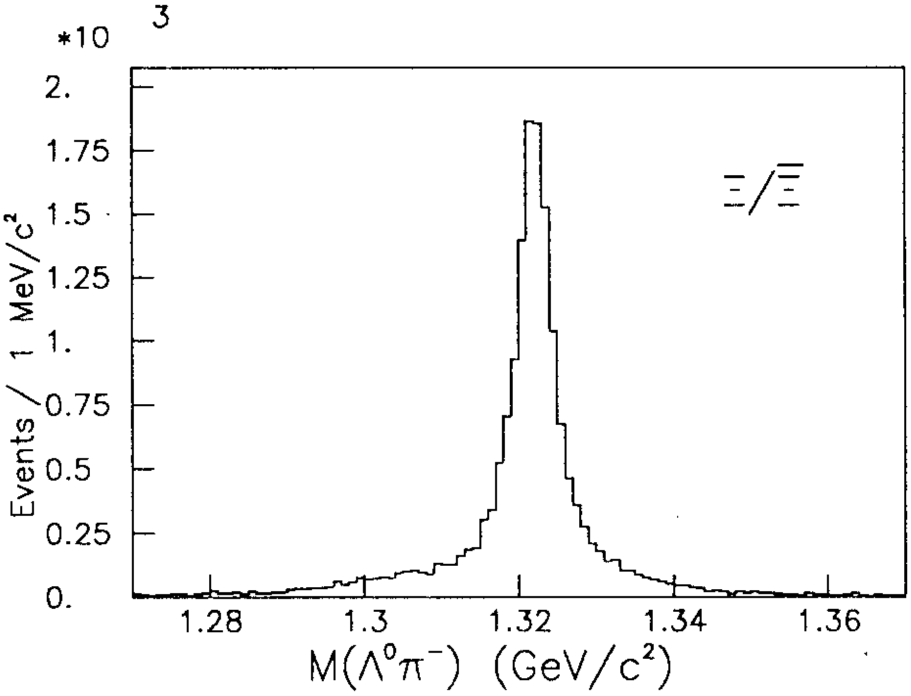
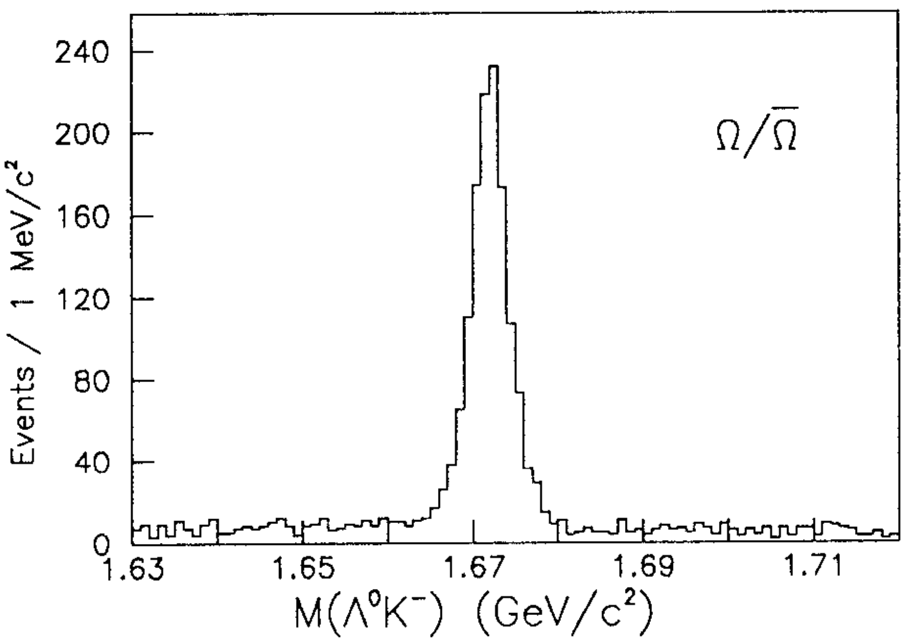

*10 3
2.
1.75
1.5
1.25
1.
0.75
0.5
0.25
0.
Events / 1 MeV/c²
1.28
1.3
1.32
1.34
1.36
M(Λ⁰π⁻) (GeV/c²)
Ξ/Ξ̄

Fig 3



240
200
160
120
80
40
0
Events / 1 MeV/c²
Ω/Ω̄
1.63
1.65
1.67
1.69
1.71
M(Λ⁰K⁻) (GeV/c²)

Fig 4