Properties of the Charmed Strange Baryon $A^+$ and Evidence for the Charmed Doubly Strange Baryon $T^0$ at 2.74 GeV/c$^2$ *)


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ABSTRACT

Results are presented from experiment WA62, which searched for charmed strange baryon states produced in \( \bar{\Xi}^- \)-nucleus interactions in the SPS charged hyperon beam at CERN. Properties of the \( A^+(csu) \) baryon at 2.46 GeV/c\(^2\) are summarized and upper limits are given for decay branching ratios into various channels. Three events observed at 2.74 GeV/c\(^2\) in the \( \bar{\Xi}^--K^+\pi^+ \) mass spectrum are interpreted as the first evidence for the \( T^0 \) baryon with quark content \( cqs \). Results of a search for the \( A^0 \) (csd), the isospin partner of the \( A^+ \), are presented. The results are discussed in the context of current theoretical understanding, and a comparison with other experiments on hadroproduction of charmed baryons is made.
1. **INTRODUCTION**

We report on the searches, carried out at CERN in experiment WA62, for the production of charmed strange baryons in $\Xi^-$-Be collisions. The use of strange baryon projectiles was expected to favour the production of charmed baryons with non-zero strangeness. Such baryons would have zero or positive charge and couple, through Cabibbo-allowed decays, to final states with strangeness -2 or -3.

First results have already been published [1,2]. In Ref. 1, evidence was presented for the production of the $A^+$ baryon (quark content csu) in the reaction

$$\Xi^- + \text{Be} \rightarrow A^+ + \text{X}.$$  

This state was observed in the $AK^-\pi^+\pi^+$ mass spectrum as a narrow peak at 2.46 GeV/c$^2$. The positive charge and strangeness -2 of this final state, and the narrow width, consistent with the resolution of the apparatus, supported the interpretation of the signal as a Cabibbo-allowed decay of a charmed strange baryon. This conclusion was further strengthened by the measured lifetime of $(4.8^{+12.9}_{-1.8}) \times 10^{-19}$ s for the events in the mass peak [2].

In this article we report results from the search for other decay modes of the $A^+$ and for other charmed strange baryons. Of particular interest is the observation of three events at 2.74 GeV/c$^2$ in the channel $K^-K^+\pi^+\pi^+$, which is interpreted as the first evidence for the charmed baryon $T^0$, with quark content css.

In Section 2 we briefly describe the apparatus, in Section 3 the trigger and the event selection and in Section 4 the Monte Carlo simulation. The production and decay properties of the $A^+$ are given in Section 5. The results of the search for the $A^0$, the isospin partner of the $A^+$, are presented in Section 6, and Section 7 is devoted to the $T^0$ analysis. In Section 8 an interpretation of the results in terms of some theoretical models is given and a comparison is made with other experiments. The results are summarized in Section 9.
2. **APPARATUS**

The apparatus was designed to accept charmed strange baryons produced in the forward direction in $\Xi^-$-Be collisions and to identify them by studying the effective mass distributions of combinations of particles.

The experiment was performed in the charged hyperon beam at the CERN SPS, which has been described elsewhere [3]. For this experiment, the beam was tuned to its maximum momentum of 135 GeV/c. A differential Cherenkov counter (DISC) selected $2 \times 10^4$ incident $\Xi^-$ in each 1.5 s beam pulse of $1.5 \times 10^6$ particles (mainly $\pi^-$. The trajectories of the beam particles were measured in multiwire proportional chambers (MWPCs) located upstream and downstream of the DISC (Fig. 1).

The $\Xi^-$ struck an 8 cm long Be target, located downstream of the DISC. Charged particles produced in the forward direction were tracked in a double magnet spectrometer equipped with MWPCs and drift chambers (DCs). In order to resolve ambiguities between closely spaced or overlapping tracks, a large number of chamber planes (46 in total) were installed between the target and the first magnet SM1. Protons, kaons and pions with sufficient momentum to pass through both magnets were identified in two multicell Cherenkov counters, C1 and C2, which had pion thresholds of 14 GeV/c and 10 GeV/c, respectively. The cell structure of these Cherenkov counters was matched by two scintillator hodoscopes H4 and H5. The additional deflection in the second magnet SM2 was sufficient to separate positive and negative charged particles at the position of H4. Further details of the apparatus are given in Refs. 1 and 2.

3. **TRIGGER AND EVENT SELECTION**

The primary aim of the trigger was to select final states of strangeness $-2$ or $-3$, with zero or positive charge. Therefore the trigger required among the produced particles, a $\Lambda$ and a $K^-$ together with at least one more charged particle. This restricted choice was made because the data recording system had a capacity of 250 events per beam spill, which at the full $\Xi^-$ rate of 20000 per spill was not sufficient to accept all possible decay channels.
The trigger requirements were:

i) A signal from a $E^-$ passing through the DISC.

ii) Signals from at least two charged particles in hodoscope H1 and at least four charged particles in H2. This requirement was met by events with two charged particles coming from the target and a $\Lambda \rightarrow p\pi^-$ decay occurring upstream of H2. At least four charged particles were also required in H3.

iii) A proton candidate, which had traversed hodoscope H5 on the "positive side" without producing Cherenkov light in the corresponding cell of C2.

iv) A $K^-$ candidate, which had traversed hodoscope H4 on the "negative side" without producing Cherenkov light in the corresponding cell of C1.

In the off-line analysis, charged particle trajectories had to come from the target or from a $V^0$ downstream of the target. For trajectories passing through SM1, the particle momenta were calculated. The $\Lambda$ and $K^0$ decays were kinematically identified by computing the $p\pi^-$ and $\pi^+\pi^-$ effective mass. For $\Lambda$ candidates, we required the computed effective mass to be within 4 MeV/c$^2$ of the $\Lambda$ mass, the width of the effective mass distribution being 1.6 MeV/c$^2$ (r.m.s.), (see Fig. 2b). The background under the $\Lambda$ signal was less than 5%. For $K^0$ candidates, the effective mass was required to be within 9 MeV/c$^2$ of the $K^0$ mass. The width of this effective mass distribution was 3.5 MeV/c$^2$ (r.m.s.), (see Fig. 2a).

The $K^-$ requirement in the trigger was strengthened off-line by combining information from both Cherenkov counters, taking into account their different thresholds. Counter C1 had a pion threshold of 14 GeV/c and reached its maximum efficiency of 97% at a pion momentum of 30 GeV/c. In order to reject pions a momentum cut at 17 GeV/c was applied to the $K^-$ candidates. At this momentum the efficiency of C1 for detecting pions was 68%. Counter C2 had a kaon threshold of 36 GeV/c. Below this momentum it was used to further reduce the pion contamination.
Charged particles which were not identified as $p$ or $K^-$ were generally taken to be pions. Cherenkov identification for these particles was not possible, as more than 90% of them had momenta less than 17 GeV/c or did not pass through SM2.

Although the trigger was designed to accept $(AK^-\pi^+ + X)$ events it was also sensitive to final states of the type $(pK^- + 2 \text{ charged} + X)$ and $(pK^-K^0 + X)$ where the decay $K^0_S \rightarrow \pi^+\pi^-$ occurred before H2. These event classes were also considered in the analysis.

4. THE MONTE CARLO SIMULATION

The acceptance and resolution of the apparatus were determined from the Monte Carlo (MC) simulation of the experiment. This included the geometrical arrangement of the detectors, their efficiencies and spatial resolutions. The multiple scattering in the material of the apparatus, and the decays of secondary particles were taken into account.

This simulation was able to reproduce the measured effective mass distributions for the decays $K^0 \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\pi^-$, $\Xi^- \rightarrow \Lambda\pi^-$ and $\Omega^- \rightarrow AK^-$ apart from small tails in the distributions which were more pronounced in the data (Fig. 2). These decays, together with the well known resonances $K^0(896)$, $\Sigma^+(1382)$ and $\Xi^0(1532)$, Fig. 3, were used to check the absolute calibration of the mass scale by studying the dependence of the reconstructed masses on the calibration constants of the magnetic field and the geometrical alignment. From the uncertainties on these quantities we determined the systematic error in the mass calibration.

The Monte Carlo program was used to determine the acceptance for the various decay modes of the $A^+$ baryon. For these calculations the $A^+$ were generated according to an invariant differential cross section of the form

$$\Sigma \frac{d^3\sigma}{dp^3} \propto (1-x)^n e^{-bp_T^2} \quad (x = p_L/p_{max}^{cm})$$
where the parameters $n$ and $b$ could be adjusted. The $A^+$ decay products were generated according to phase space, but sequential decays via resonances could also be introduced. Figure 4 shows the acceptance of the apparatus for the channel $AK^-\pi^+\pi^+$ as a function of the $A^+$ longitudinal momentum, for a $p_T$ distribution with the experimental value $b = -1.1$ (see Section 5.1). For a given $p_L$, variations of $b$ within the experimental limits would change the acceptance by less than 20%.

5. INVESTIGATION OF THE $A^+$

5.1 The $AK^-\pi^+\pi^+$ decay channel

Events were selected if they had a $\Lambda$, a $K^-$ meson and at least two additional positive particles (assumed to be pions). The tracks of the $K^-$ and both $\pi^+$ had to intersect the $\Sigma^-$ trajectory in the target region with a closest distance of approach of less than 2 mm.

The $AK^-\pi^+\pi^+$ effective mass distribution shows a prominent peak which is contained in two bins of 15 MeV/c$^2$ centred at 2460 MeV/c$^2$ (Fig. 5). This peak was interpreted as a Cabibbo-allowed decay of the charmed strange baryon $A^+$.

The signal contains 82 events above a background estimated to be $147 \pm 5$. The width of the peak is $(21^{+7}_{-4})$ MeV/c$^2$ (FWHM). The mass resolution of the apparatus was determined with the Monte Carlo program to be $(22 \pm 2)$ MeV/c$^2$ (FWHM), which gives an upper limit on the intrinsic width, $\Gamma < 20$ MeV/c$^2$ (90% CL). The mass of the new particle is $(2460 \pm 15)$ MeV/c$^2$, where the error is dominated by the systematic uncertainty in the mass scale.

Anticharmed mesons produced in association with the $A^+$ could not be identified, since only decays not involving neutral particles could be completely measured and since the branching ratios for such decay channels are of the order of a few percent. Furthermore, as the mean momentum of the observed $A^+$ was 90 GeV/c, the associated mesons must have had much lower momenta, at which the spectrometer acceptance was small, even if their decay particles were only required to pass through SML. For example, the acceptance was 1% for $D^-$ carrying half the momentum difference between $\Sigma^-$ and $A^+$ and decaying via $D^- \rightarrow K^+\pi^-\pi^-$. 
The lifetime of the $A^+$ was determined from the distribution of the distances between the production and decay vertices. The decay vertex was defined by the intersection of the $K^-$ and the two $\pi^+$ tracks. The production vertex was determined from the intersection of the beam track with additional tracks not participating in the $\Lambda K^-\pi^+\pi^+$ mass combination. Stringent geometrical criteria were applied in this reconstruction (Ref. 2) resulting in a resolution of 6 mm (r.m.s.) on the distance between vertices. After this selection a signal of 53 events remained above a background of 59. The value obtained for the lifetime is $(4.8^{+2.9}_{-1.8}) \times 10^{-13}$ s where the error on the positive side takes into account the possibility that tracks from the decay of associated $D$ mesons were included in the reconstruction of the production vertex.

The invariant cross section for $A^+$ production was found to be adequately described by the form

$$E \frac{d^3\sigma}{dp^3} = (1 - x)^n e^{-bP_T^2}$$

in the region $x > 0.6$, corresponding to $P_T > 82$ GeV/c, where the signal contained 60 events above a background of 96. This cutoff was chosen to avoid the large acceptance corrections at lower momenta (Fig. 4). From a fit to the data we obtained $n = 1.7 \pm 0.7$ and $b = (1.1^{+0.7}_{-0.4}) (\text{GeV/c})^{-2}$.

The product of cross section and branching ratio for the observed decay mode $A^+ \rightarrow \Lambda K^-\pi^+\pi^+$ was found to be

$$\sigma \cdot B = (5.3 \pm 2.0) \mu b/\text{Be nucleus} \quad \text{for } x > 0.6.$$ 

5.2 Other $A^+$ decay channels

The number of $A^+$ decay channels which could be investigated in this experiment was restricted by the lack of a neutral particle detector and by the trigger requirement of a proton, a $K^-$ and at least two additional
charged particles. The decay modes $\Lambda K^{-} \pi^{+} \pi^{+}$ ($\Lambda \to p\pi^{-}$), $pK^{-}K^{0}\pi^{+}$ ($K^{0}_{S} \to \pi^{+}\pi^{-}$), $pK^{-}K^{+}\pi^{+}$ and $\Omega^{-}K^{+}\pi^{+}$ ($\Omega^{-} \to \Lambda K^{+}$) were therefore the only Cabibbo-allowed ones to which the experiment was sensitive. For decay channels with higher charged multiplicities, e.g. with additional $\pi^{+}\pi^{-}$ pairs, the acceptance dropped rapidly. The relative acceptances for the different decay modes were calculated using the Monte Carlo program. No cut on $p_{L}$ was applied to the Monte Carlo or data samples.

5.2.1 The $pK^{-}K^{0}\pi^{+}$ channel

The effective mass distribution for this channel is shown in Fig. 6. The two 15 MeV/$c^{2}$ bins around the $A^{+}$ mass together contain 36 events. An estimation of the background level, made by averaging over five channels on each side of the signal bins, yields $45 \pm 3$ events. If one shifts the background window on the low-mass side downwards by three bins, to avoid including the bump just above 2400 MeV/$c^{2}$, the linear interpolation gives $37 \pm 3$ events. The value adopted is $41 \pm 4$ events where the error has been increased to take into account possible non-linearities in the background distribution.

The acceptance for this decay mode relative to the $\Lambda K^{-} \pi^{+} \pi^{+}$ mode was $1.33 \pm 0.05$, where the error reflects the uncertainty on the shape of the $A^{+}$ momentum spectrum. With the branching ratios $BR(\Lambda \to p\pi^{-}) = 0.642$ and $BR(K^{0}_{S} \to \pi^{+}\pi^{-}) = 0.5 \times 0.686$ we obtained

$$\frac{\Gamma(\Lambda^{+} \to pK^{-}K^{0}\pi^{+})}{\Gamma(\Lambda^{+} \to \Lambda K^{-} \pi^{+} \pi^{+})} < 0.08 \ (90\% \ CL).$$

5.2.2 The $pK^{-}K^{-} \pi^{+} \pi^{+}$ channel

The distribution of the $pK^{-}K^{-} \pi^{+} \pi^{+}$ effective mass, requiring only one of the $K^{-}$ to be identified in the Cherenkov counters, is shown in Fig. 7. No signal is visible in the two bins around 2460 MeV/$c^{2}$ which together contain 20 events. The shape of the background cannot be described by a linear approximation. A polynomial fit results in a background estimate of $24 \pm 10$ events, where the error takes into account the systematic uncertainties from the choice of the background window and the order of the
polynomial. The relative acceptance for this decay mode was $2.88 \pm 0.02$. This yields, together with the branching ratio for the $A \rightarrow p\pi^-$ decay, an upper limit

$$\frac{\Gamma(A^+ \rightarrow pK^-\pi^-\pi^+)}{\Gamma(A^+ \rightarrow AK^-\pi^+\pi^+)} < 0.03 \ (90\% \ CL).$$

Requiring the second $K^-$ candidate to be identified by the Cherenkov counters reduces the acceptance by a factor of about 6. The observed spectrum contains one event in the signal region with an estimated background of one, resulting in a similar upper limit.

5.2.3 The $\Omega^-K^+\pi^+$ channel

The phase space for this decay channel is much smaller than for those discussed above. No $A^+$ signal was found in the $\Omega^-K^+\pi^+$ effective mass distribution. Because the $A^+$ mass is very close to the threshold of this channel, the acceptance calculation had large uncertainties arising from reconstruction losses for very close tracks. Therefore we do not give an upper limit for the relative branching ratio of this decay mode.

5.2.4 The $\Lambda K^0(896)\pi^+$ and $\Sigma^+(1382)K^-\pi^+$ channels

We have looked for $K^*$ and $L^*$ contributions to the $\Lambda K^-\pi^+\pi^+$ final state. Figure 8 shows the $K^-\pi^+$ and $A\pi^+$ effective mass distributions from the events in the $A^+$ signal, after a background subtraction using events in neighbouring bins. As the final state contains two $\pi^+$, every event gives two combinations in each plot. Also shown are the distributions expected for the four-body phase-space decay $A^+ \rightarrow \Lambda K^-\pi^+\pi^+$ (smooth curves) and for the three-body phase-space decays $A^+ \rightarrow \Lambda K^0(896)\pi^+$ and $A^+ \rightarrow \Sigma^+(1382)K^-\pi^+$, respectively (dashed curves).

From a comparison of the data with these expected distributions we obtained a value of $0.30 \pm 0.30$ for the $K^*$ contribution and a value of $0 \pm 0.18$ for the $L^*$ contribution to the final state, which yield upper limits of 0.7 and 0.25, respectively, at the 90% confidence level.
6. SEARCH FOR A⁰ DECAYS

In this section we describe the search for the A⁰ (quark content csd), the isospin partner of the A⁺. Their masses are expected to be equal to within a few MeV/c².

The A⁰ decay most similar to the observed decay A⁺ → AK⁻π⁺π⁺, would be A⁰ → AK⁻π⁺π⁰. Due to the lack of γ detectors, this decay could not be detected in our experiment. However the apparatus was sensitive to the decay A⁰ → AK⁻π⁺. The distribution of the AK⁻π⁺ effective mass is shown in Fig. 9, which contains 22884 combinations from 19086 events. The selection criteria for the events in this figure were the same as those used for the AK⁻π⁺π⁺ effective mass distribution (Fig. 5) except for the number of positive pions. There are 582 combinations in the two mass bins centred at 2460 MeV/c². The line represents a polynomial fit of order 2, which resulted in a background estimation of 580 ± 15, where the error includes the uncertainties from the choice of the background windows for the fit. This gives an excess of 2 ± 28 events at the expected A⁰ mass. We can therefore set an upper limit of 38 events (90% CL) for the decay A⁰ → AK⁻π⁺ with a mass of 2460 MeV/c². If x > 0.6 is required, as in the determination of the A⁺ production cross section, the excess is 9 ± 26 events, resulting in a similar upper limit.

The application of the vertex criteria, used for the determination of the A⁺ lifetime, reduced the background level by approximately a factor of 2. Even under these conditions no A⁰ signal was seen.

Other Cabibbo-favoured decay channels of the A⁰, to which the apparatus was sensitive, were Ω⁻K⁺ (Ω⁻ → AK⁻), pK⁻K⁻π⁺ and pK⁻K⁰ (Kₛ⁻ → π⁺π⁻). In none of these channels was an A⁰ signal observed.

Assuming the same x and pₜ dependence for A⁰ production as observed in A⁺ production (cf. Section 5.1), we derived an upper limit on the product of cross section and branching ratio for the reaction Σ⁻ + Be → A⁰ + K, A⁰ → AK⁻π⁺ for x > 0.6:
\[ \sigma \cdot b < 3.8 \, \mu b/\text{Be nucleus (90\% CL).} \]

This number does not change significantly if \( n \) and \( b \) are varied within the experimental errors found for \( A^+ \) production. It may be expected, however, that in \( \Sigma^- N \) collisions \( A^0 \) are produced with higher momenta than \( A^+ \), because the \( A^0 \) can contain two quarks from the incident \( \Sigma^- \), but the \( A^+ \) only one. If, for example, we use \( n = 1 \) for \( A^0 \) production and the observed value \( n = 1.7 \) for \( A^+ \) production, the upper limit decreases to 3.4 \( \mu b/\text{Be nucleus} \). This limit also is insensitive to changes of \( n \) and \( b \) within the experimental errors, provided the difference \( n(A^0) - n(A^+) \) is kept constant.

7. **FIRST OBSERVATION OF THE \( T^0(\text{css}) \) BARYON**

In this section a study of final states with strangeness \( S = -3 \) and charge \( Q = 0 \) is presented.

As described in Ref. 1 the \( S = -2 \) assignment of the \( A^+ \) signal in the \( \Lambda K^+ \pi^+ \pi^+ \) effective mass distribution was checked by computing the effective mass under various assumptions for the mass assignments to the charged tracks. The events in the \( A^+ \) signal bins did not show significant structure in any other mass combination. This demonstrated that the \( A^+ \) was not a "reflection" of another state.

In cases where the \( A \) resulted from the decay \( \Xi^- \rightarrow A\pi^- \), its observation in association with a \( K^- \) would indicate an \( S = -3 \) final state. Using the same sample of events that yielded the \( A^+ \) signal, a search was made for events in which an additional negative track intersected the \( A \) line of flight downstream of the target with a closest distance of approach of less than 1.5 mm. Figure 10 shows the effective \( A\pi^- \) mass distribution obtained when this extra track was interpreted as a \( \pi^- \). A clear signal of 20 events is visible within \( \pm 7 \) MeV/c\(^2 \) of the \( \Xi^- \) mass. None of these events contributed a \( \Lambda K^+ \pi^+ \pi^+ \) mass combination to the \( A^+ \) peak.

The \( \Xi^- K^+ \pi^+ \pi^+ \) effective mass was calculated for these 20 events, which yielded 26 such combinations (Fig. 11a). These events were subjected to a detailed analysis. Figure 11b shows the mass distribution for events which
had additional tracks in the chambers B, C and D1 thereby permitting the reconstruction of the production vertex. This requirement was suggested by the observation that the ratio of signal to background for the $A^+ \rightarrow AK^- \pi^+ \pi^+$ channel increased from 82/147 to 53/59 (see Section 5.1) when the same condition was imposed. This sample contained 15 combinations from 10 events.

The events shown in Fig. 11c were required to have a $K^- \pi^+$ combination with an effective mass compatible with a $K^0(896)$, i.e. $0.85 < M(K^- \pi^+) < 0.95 \text{ GeV}/c^2$. Ten combinations from seven events remain. The main motivation of this requirement was to strengthen the $S = -3$ assignment of the final state by removing $K^+$ and $\pi^-$ which had been misidentified as $\pi^+$ or $K^-$, respectively.

The events shown in Fig. 11d were required to have an $E^- \pi^+$ combination with an effective mass consistent with a $E^0(1532)$, i.e. $1515 < M(E^- \pi^+) < 1545 \text{ MeV}/c^2$. Eight combinations from six events satisfied this criterion.

The requirement of both a reconstructed production vertex and a $K^0(896)$ resulted in a $E^-K^- \pi^+ \pi^+$ effective mass distribution (Fig. 12) with six combinations from four events. The properties of these events are summarized in Table 1. Three events have a mass combination near 2740 MeV/c$^2$ where the mass of the $T^0$ is expected (see Ref. 4, for example).

The spread of the masses of the three events around 2740 MeV/c$^2$ is fully compatible with the mass resolution of the apparatus, which we estimated from Monte Carlo calculations to be 25 MeV/c$^2$ (FWHM). The mass of this state was determined to be $(2740 \pm 25)$ MeV/c$^2$, where the error was dominated by the systematic uncertainty in the mass scale.

The reconstructed production vertex in these events allowed a measurement of the distance $\Delta z$ between the production and the decay of the $E^-K^- \pi^+ \pi^+$ system with a resolution of 6 mm (r.m.s.). A mean $\Delta z$ of this magnitude would correspond to a $T^0$ lifetime of about $6 \times 10^{-13}$ s. Two of the combinations (shown shaded in Fig. 12) have negative values of $\Delta z$, corresponding to a reconstructed decay vertex upstream of the reconstructed production vertex. On the other hand $\Delta z$ is positive for all three combinations with a mass near 2740 MeV/c$^2$, the $\Delta z$ values being 2, 0.5 and 1.5.
standard deviations away from zero, respectively. This is an indication that these events result from a weak decay. We therefore conclude that we have observed evidence for the T^0 baryon decaying in a Cabibbo-favoured mode.

The number of events is too small to allow an estimate of the T^0 production cross section, because calculation of the acceptance of the apparatus requires knowledge of the T^0 momentum spectrum at production, and moreover the branching ratio of \( T^0 \rightarrow \Sigma^- K^+(896)\pi^+ \) is unknown. However, it is worthwhile to make some qualitative comments on the T^0 cross section. Assuming similar momentum spectra for the T^0 and the A^+, the acceptance of the apparatus for the T^0 is approximately one half that for the A^+, mainly because of the additional \( \Sigma^- \) decay length. Furthermore it can be expected that in \( \Sigma N \) collisions T^0 are produced with a lower rate than A^+ because of the additional strange quark contained in the T^0. In 200 GeV/c pN collisions, for example, the ratio of \( \Sigma^- \) and \( \Sigma^+ \) produced at \( x = 0.66 \) is 20 [3]. Therefore the observation of three T^0 decays, as compared to 53 A^+ decays is not unreasonable.

The experiment was sensitive to three other Cabibbo-allowed T^0 decay channels: \( \Omega^- \pi^+ \), \( \Omega^- \pi^+ \pi^- \pi^+ \) and \( \Lambda K^- \pi^+ \pi^+ \). None of these effective mass distributions showed a T^0 signal.

8. DISCUSSION

In this section we discuss the results for the A^+ and T^0 masses, the A^+ lifetime and the A^+ production and compare them with results from other experiments and with theoretical predictions. The only other charmed baryons observed up to now are the \( \Lambda_c^+ \), \( \Sigma_c^+ \), and \( \Sigma_c^0 \). Only nine \( \Sigma_c \) events have been observed (8 \( \Sigma_c^{++} \), 1 \( \Sigma_c^+ \)) [5]. The \( \Lambda_c^+ \), on the other hand, has been observed in many experiments and in various decay modes [5]. However, even here our knowledge is still poor; for example, the sum of the measured branching ratios is less than 10% and experiments disagree on the value of the mass.

In the present experiment, the known \( \Lambda_c^+ \) decay modes (\( \Lambda_c^+ \pi^+ \pi^- \), \( \Sigma_c^0 \pi^+ \), \( pK^- \pi^- \), \( pK^- \pi^+ \), Ref. 5) were suppressed by the trigger which required at least four charged particles, including a \( K^- \) candidate. For the possible sequential decay \( \Sigma_c^0 \rightarrow \Lambda_c^+ \pi^- \), \( \Lambda_c^+ \rightarrow pK^- \pi^+ \), the acceptance was very small.
8.1 Masses

Much theoretical work on charmed baryons has been devoted to the calculation of their masses. Most authors used the then current value of the $\Lambda_c^+$ mass to fix their mass scale. It is therefore more meaningful to consider the mass differences between $\Lambda_c^+$, $A^+$, and $T^0$ instead of the absolute values. We use the 1984 world average of the $\Lambda_c^+$ mass, $m = (2282 \pm 3)$ MeV/c$^2$ [5] to calculate mass differences $\Delta m (\Lambda_c^+, A^+)$ and $\Delta m (\Lambda_c^+, T^0)$. It should be kept in mind, however, that the experimental situation with respect to the $\Lambda_c^+$ mass is not yet satisfactory.

In Table 2 various predictions for the mass differences between $\Lambda_c^+$, $A^+$ and $T^0$ are compiled [6]. Three of these predictions [6a,6c,6d] are in agreement with the experimental values for both $A^+$ and $T^0$.

8.2 $A^+$ Lifetime

The measured $A^+$ lifetime $(4.8^{+2.9}_{-1.8}) \times 10^{-13}$ s is of the magnitude expected for charmed particles [7]. The lifetime of the $\Lambda_c^+$ is $(2.2^{+0.7}_{-0.4}) \times 10^{-13}$ s [8] based on 19 events observed in three different experiments.

The weak decay of charmed particles is commonly classified into spectator and non-spectator processes (Fig. 13). If the spectator processes were dominant, one would expect the lifetimes of all singly charmed hadrons to differ only by phase space corrections. The importance of the non-spectator processes in the decay of charmed particles is supported by the observed differences between the lifetimes of the charged and neutral D mesons, $\tau_D^+ = (9.2^{+1.7}_{-1.2}) \times 10^{-13}$ s and $\tau_D^0 = (4.4^{+0.8}_{-0.6}) \times 10^{-13}$ s [5]. The $D^+$ can decay only via the spectator process $c \to u d \bar{u}$, whereas the $D^0$ can also decay via the exchange process $c \to s d \bar{u}$.

The $\Lambda_c^+$ decay can occur via the exchange process $c d \to u s$, whereas for the Cabibbo-allowed decays of the $A^+$ and the $T^0$ only spectator processes are
possible. Therefore the lifetime of the $A^+$ is expected to be larger than the lifetime of the $A^+_c$, two theoretical estimates for the ratio of the $A^+$ and $A^+_c$ lifetimes being 2.5 [4] and 4 [9]. This tendency is supported by the measured values. In the case of the $\Upsilon^0$ the decay lengths of the events suggest a lifetime larger than the $A^+_c$ lifetime, in agreement with the above arguments.

8.3 $A^+$ production

The $A^+$ was observed in the reaction $\Sigma^- + \text{Be} \rightarrow A^+ + X$ via its decay into $AK^-\pi^+\pi^+$. In the region $x > 0.6$, where the experiment was sensitive, the production cross section times branching ratio, $\sigma \cdot B$, for this process was measured to be

$$\sigma \cdot B = (5.3 \pm 2.0) \text{ mb/Be nucleus}$$

A reliable estimate of the total cross section for the production of $A^+$ in $\Sigma^-$-nucleon reactions is not possible with the present knowledge of charmed baryon production and decay. Such an extrapolation would be very model-dependent and the result could vary by more than one order of magnitude. The three main problems are:

i) The cross section has to be extrapolated from the $x$ region where the experiment was sensitive to the whole region $-1 \leq x \leq 1$. In the region $x > 0.6$, the invariant cross-section for $A^+$ production with incident $\Sigma^-$ is reasonably well described by $(1-x)^{1.7 \pm 0.7}$. However, an extrapolation based on this formula would be unreliable in the region of lower $x$, where the production processes could be quite different.

ii) The cross section per nucleon has to be calculated from the measured cross section per nucleus. It is usually assumed that these cross sections are related by a factor $A^\alpha$, where $A$ is the atomic mass number. Little is known about the $A$ dependence of open charm production. Generally a value of $\alpha = 1$ as observed in $J/\psi$ production has been used. However, data on prompt neutrino production indicate a value near $\alpha = 2/3$ [10]. Furthermore, $\alpha$ may vary with $x$ as observed in inclusive hadron fragmentation for non-charm processes, where $\alpha$
was found to change by more than a factor 1.5 between $x = 0$ and $x = 1$ [11].

iii) There is no information on the decay branching ratios. The branching ratio for the decay $A^+ \rightarrow \Lambda K^+ \pi^+ \pi^+$ is unmeasured and there are no quantitative theoretical predictions for the decays of charmed baryons into multiparticle final states.

Other experiments on hadroproduction of charmed baryons share these difficulties to a greater or lesser extent. Therefore caution should be exercised in comparing the results of different experiments.

In view of these difficulties, we compare our experiment on $A^+$ production in $\Sigma^-$ Be collisions only with similar experiments on $\Lambda^+_c$ production in nucleon-nucleus collisions. There are two experiments with $x$-range, target materials and centre of mass energies relatively close to those studied in our experiment, viz. BIS-2 [12] which studied inclusive $\Lambda^+_c$ production at Serpukhov, and NA11 [13] which studied associated $\Lambda^+_c D$ production at CERN (see Table 3).

The measured values of $\sigma \cdot B$ reported by BIS-2 and by our experiment are similar in magnitude, despite the different beam projectiles and the three unknown, and possibly different, branching ratios involved. The upper limit given in Table 3 for the NA11 experiment was calculated from their published limit of $\sigma(\Lambda^+_c) \leq 8 \mu b$/nucleon, using information given in the paper. However, this result involves a fourth decay channel, and it depends strongly on the assumed dynamics of the associated production of a $\Lambda^+_c$ and a $D$ meson. Given the values of $\sigma \cdot B$ listed in Table 3 and the various problems elaborated above, it is difficult to understand the conclusion drawn by the NA11 group in Ref. 12, that their limit is in agreement with the BIS-2 results, but cannot be reconciled with ours.

9. SUMMARY

We have reported the results of an experiment on the production of charmed strange baryons in a high-energy hyperon beam. The discovery of
the $A^+(csu)$ and the first evidence for the $I^0$ (css) show the potential of this technique. The measurement of the $A^+$ lifetime demonstrates that charmed particle lifetimes are accessible in fixed target experiments using wire chambers for track detection.

The following results were obtained for the production of the $A^+$ in the reaction $\Xi^- + Be \to A^+ + \pi^-$, $A^+ \to \Lambda K^- \pi^+$, at $\sqrt{s} = 16$ GeV:

$$E \frac{d^3\sigma}{dp^3} = (1-x)^{1.7\pm0.7} \times e^{-(1.1^{+0.7}_{-0.4})} p_T$$

$$\sigma\cdot B = (5.3 \pm 2.0) \mu b/Be \text{ nucleus for } x > 0.6 .$$

The mass and lifetime of the $A^+$ were measured to be

$$m_{A^+} = (2460 \pm 15) \text{ MeV/c}^2$$

$$\tau_{A^+} = (4.8^{+2.9}_{-1.0}) \times 10^{-13} \text{ s} .$$

Upper limits at the 90% confidence level were found for the branching ratios of the following decay modes:

$$\frac{\Gamma(A^+ \to \Lambda K^-(896)\pi^+)}{\Gamma(A^+ \to \Lambda K^- \pi^+ \pi^+)} < 0.7$$

$$\frac{\Gamma(A^+ \to \Sigma^+(1382)K^-\pi^+)}{\Gamma(A^+ \to \Lambda K^- \pi^+ \pi^+)} < 0.25$$

$$\frac{\Gamma(A^+ \to pK^- \pi^+ \pi^+)}{\Gamma(A^+ \to \Lambda K^- \pi^+ \pi^+)} < 0.03$$

$$\frac{\Gamma(A^+ \to pK^- \bar{\nu}_\pi^+)}{\Gamma(A^+ \to \Lambda K^- \pi^+ \pi^+)} < 0.08$$

An upper limit was found for the production of the $A^0$ in the process $\Xi^- + Be \to A^0 + \pi^-$, $A^0 \to \Lambda K^- \pi^+$

$$\sigma\cdot B < 3.8 \mu b/Be \text{ nucleus (90\% C.L.) for } x > 0.6 .$$

The mass of the $I^0$ was measured to be

$$m_{I^0} = (2740 \pm 25) \text{ MeV/c}^2.$$
Acknowledgements

We wish to thank J. Zimmer and R. Schillcott for their contributions at various stages of the experiment. We are especially grateful for the support we have received from members of the different workshops at each of our laboratories. We gratefully acknowledge the support of the CERN EA group and the SPS crew, who helped to make this experiment possible in the short running time available. One of us (S.N.T.) thanks the Australian Research Grants Scheme for financial support.
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[9] R. Rückl, Weak decays of heavy flavours, Habilitationsschrift,


Table 1

The properties of the events in Fig. 12. For each $E^{-}K^{-}\pi^{+}\pi^{+}$ combination, the values of the $K^{-}\pi^{+}$ and the $E^{-}\pi^{+}$ effective mass are given for both $\pi^{+}$, the values in brackets corresponding to that $\pi^{+}$, which is not compatible with $K^{0}(896)$ decay. $\Delta z$ is the distance between the production and the decay of the $E^{-}K^{-}\pi^{+}\pi^{+}$ system, positive $\Delta z$ corresponding to a reconstructed decay vertex downstream of the reconstructed production vertex.

<table>
<thead>
<tr>
<th>Event number</th>
<th>$m(E^{-}K^{-}\pi^{+}\pi^{+})$ (MeV/c$^{2}$)</th>
<th>$m(K^{-}\pi^{+})$ (MeV/c$^{2}$)</th>
<th>$m(E^{-}\pi^{+})$ (MeV/c$^{2}$)</th>
<th>$p$ (GeV/c)</th>
<th>$p_{t}$ (GeV/c)</th>
<th>$\Delta z$ (mm)</th>
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<tr>
<td>1</td>
<td>2745</td>
<td>890 (970)</td>
<td>1648 (1663)</td>
<td>107.7</td>
<td>0.51</td>
<td>+12</td>
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<tr>
<td></td>
<td>2588</td>
<td>890 (754)</td>
<td>1648 (1474)</td>
<td>106.1</td>
<td>0.72</td>
<td>-12</td>
</tr>
<tr>
<td>2</td>
<td>2738</td>
<td>944 (807)</td>
<td>1795 (1611)</td>
<td>81.9</td>
<td>0.76</td>
<td>+3</td>
</tr>
<tr>
<td>3</td>
<td>3404</td>
<td>877 (1095)</td>
<td>1541 (2440)</td>
<td>85.6</td>
<td>0.54</td>
<td>+8</td>
</tr>
<tr>
<td></td>
<td>2741</td>
<td>877 (717)</td>
<td>1541 (1713)</td>
<td>63.8</td>
<td>1.26</td>
<td>+9</td>
</tr>
<tr>
<td>4</td>
<td>3574</td>
<td>932 (1377)</td>
<td>1806 (2200)</td>
<td>128.8</td>
<td>0.16</td>
<td>-30</td>
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</table>

Table 2

Comparison of mass differences predicted by various models with experimental results (units are MeV/c$^{2}$)

<table>
<thead>
<tr>
<th>Authors [Ref. 6]</th>
<th>$\Delta m(A_{c}^{+}, A_{c}^{+})$</th>
<th>$\Delta m(A_{c}^{+}, T^{0})$</th>
<th>$\Delta m(A_{c}^{+}, T^{0})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>De Rujula et al. (1975)</td>
<td>220</td>
<td>480</td>
<td>260</td>
</tr>
<tr>
<td>Fuchs and Scadron (1979)</td>
<td>110</td>
<td>550</td>
<td>440</td>
</tr>
<tr>
<td>Körner et al. (1979)</td>
<td>210</td>
<td>470</td>
<td>260</td>
</tr>
<tr>
<td>Maltman and Isgur (1980)</td>
<td>220</td>
<td>470</td>
<td>250</td>
</tr>
<tr>
<td>Sakharov (1980)</td>
<td>235</td>
<td>500</td>
<td>265</td>
</tr>
<tr>
<td>Vaisenberg (1982)</td>
<td>110</td>
<td>470</td>
<td>360</td>
</tr>
<tr>
<td>Richard and Taxil (1983)</td>
<td>180</td>
<td>380</td>
<td>200</td>
</tr>
<tr>
<td>This experiment</td>
<td>$180 \pm 15$</td>
<td>$460 \pm 25$</td>
<td>$280 \pm 25$</td>
</tr>
</tbody>
</table>
Table 3

Results on charm production by baryons in beryllium and carbon

<table>
<thead>
<tr>
<th>Group</th>
<th>Reaction</th>
<th>√s [GeV]</th>
<th>x</th>
<th>σ* B [µb per nucleus]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIS-2</td>
<td>n + C → Λ_c^+ + X</td>
<td>10</td>
<td>&gt; 0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>→ pK^−π^+π^-</td>
<td></td>
<td></td>
<td>10 ± 4</td>
</tr>
<tr>
<td></td>
<td>→ Λπ^+π^-π^-</td>
<td></td>
<td></td>
<td>2.3 ± 1.1</td>
</tr>
<tr>
<td>NA11</td>
<td>p + Be → Λ_c^+ + D + X</td>
<td>17</td>
<td>&gt; 0.1</td>
<td>≤ 1.6 *)</td>
</tr>
<tr>
<td></td>
<td>→ pK^-π^+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This experiment</td>
<td>Σ^- + Be → Λ_c^+ + X</td>
<td>16</td>
<td>&gt; 0.6</td>
<td>5.3 ± 2.0</td>
</tr>
<tr>
<td></td>
<td>→ ΛK^-π^-π^+</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*) Calculated from the numbers given in Ref. 12. The authors quote an upper limit on the cross-section of 8 µb/nucleon, assuming a linear A dependence of the cross section per nucleus and a branching ratio of (2.2 ± 1.0)% for the decay Λ_c^+ → pK^-π^+. 
Figure captions

Fig. 1: Schematic layout of the apparatus. A, B, C, D, E, F = clusters of MWPCs; DC = clusters of drift chambers; SM1 and SM2 = magnets; C1, C2 = gas Cherenkov counters; H1–H5 = scintillator hodoscopes; $I^-$ = incident hyperon beam.

Fig. 2: Reconstructed masses for $K^0 \rightarrow \pi^+\pi^-$, $A \rightarrow p\pi^-$, $\Xi^0 \rightarrow \Lambda\pi^-$ and $\Omega \rightarrow \Lambda K^-$ decays. The histograms show the data, the curves the MC predictions. The MC curves have been centred on the experimental distributions.

Fig. 3: Reconstructed masses for $K^0(896) \rightarrow K^-\pi^+$, $\Sigma^+(1382) \rightarrow \Lambda\pi^+$ and $\Xi^0(1532) \rightarrow \Xi^-\pi^+$ decays. The lines are drawn to guide the eye. The arrows indicate the resonance masses.

Fig. 4: Calculated acceptance as function of the $A^+$ longitudinal momentum $p_L$ for the decay $A^+ \rightarrow \Lambda K^-\pi^+\pi^+$.

Fig. 5: The $\Lambda K^-\pi^+\pi^+$ effective mass distribution. Crosses with error bars are data. The line is a fit of a polynomial of order 3. A Gaussian with a width equal to the experimental resolution and an area equal to the observed number of events was added to the polynomial curve.

Fig. 6: The $pK^0 K^+\pi^+$ effective mass distribution.

Fig. 7: The $pK^- K^+\pi^+$ effective mass distribution.

Fig. 8: Effective masses for the events in the $A^+$ mass peak of Fig. 5 after background subtraction. Smooth lines show the MC prediction for four-body phase-space decay. a) $(K^-\pi^+)$ effective mass. The dashed curve corresponds to $A^+ \rightarrow \Lambda K^0(896)\pi^+$ decays. b) $(\Lambda\pi^+)$ effective mass. The dashed curve corresponds to $A^+ \rightarrow \Sigma^+(1382)K^-\pi^+$ decays.
Fig. 9 : The $AK^-\pi^+$ effective mass distribution.

Fig. 10 : The $\Lambda\pi^-$ effective mass distribution for events in Fig. 5 with a $\Lambda\pi^-$ interaction vertex downstream of the target.

Fig. 11 : The $\Xi^-K^-\pi^+\pi^+$ effective mass distributions. a) All events. b) Events for which the interaction vertex was reconstructed. c) Events which were compatible with the decay $K^0 \rightarrow K^-\pi^+$. d) Events which were compatible with the decay $\Xi^0 \rightarrow \Xi^-\pi^+$.

Fig. 12 : The $\Xi^-K^-\pi^+\pi^+$ effective mass distribution for $T^0$ candidates. The four events are numbered to indicate their combinatorial entries into this plot. Hatched entries have negative $\Delta z$.

Fig. 13 : Diagrams contributing to the Cabibbo-favoured decays of charmed particles. a) Spectator diagram. b) Exchange diagram. c) Annihilation diagram.
Fig. 2
Fig. 3
Fig. 4
Fig. 5

Fig. 6
Fig. 7
Fig. 8
Fig. 12

$\Xi^- K^- \pi^+ \pi^+$

Combination / 15 MeV/$c^2$

Effective Mass (MeV/$c^2$)
Fig. 13