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OBSERVATION OF A NARROW STATE AT 2.46 GeV/c² -
A CANDIDATE FOR THE CHARMED STRANGE BARYON Λ^+ *)

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ABSTRACT

A narrow state has been observed in the reaction $\Sigma^- + \text{Be} \rightarrow (\Lambda K^- \pi^+ \pi^+) + X$ in an experiment at the CERN SPS hyperon beam. At $2.46 \text{ GeV}/c^2$ the effective $(\Lambda K^- \pi^+ \pi^+)$ mass distribution shows an excess of 82 events above a background estimated to be 147, corresponding to a statistical significance of more than 6 standard deviations. The positive charge of the observed final state, which has strangeness -2, suggests the interpretation as a Cabibbo-favoured decay of the charmed strange baryon, Λ_c^+ [quark content (csu)]. The cross section times branching ratio is measured to be $\sigma \cdot B = (5.3 \pm 2.0) \text{ } \mu\text{b}/(\text{Be nucleus})$ for $x > 0.6$. The invariant production cross section is described by

$$E \frac{d^3\sigma}{d\vec{p}^3} \propto (1-x)^{(1.7 \pm 0.7)} e^{-(1.1^{+0.7}_{-0.4})p_T^2} .$$

In recent years many experiments have been undertaken to study charmed particles; however our knowledge of particles with open charm is still limited to the D , D^* , and F mesons and the Λ_c and Σ_c non-strange baryons¹⁾. By using a hyperon beam, i.e. starting with strange baryon projectiles, access into the domain of charmed strange baryons should be possible.

We report here on an experiment at the CERN SPS hyperon beam which searched for charmed strange baryons in Σ^- nucleon collisions. Such particles would have zero or positive charge and their Cabibbo-favoured decays would result in final states with strangeness -2. This experiment was devoted to the study of final states which included a K^- and a Λ accompanied by at least one other charged particle. This choice had the advantage that the proton from the $\Lambda \rightarrow p\pi^-$ decay and the K^- could be identified by Cerenkov counters and therefore selected at the trigger level.

A schematic view of the apparatus is shown in Fig. 1. A detailed description of the hyperon beam and of the DISC Cerenkov counter is given elsewhere²⁾. The beam was tuned to its maximum momentum of 135 GeV/c and at this setting the DISC selected 2×10^4 incident Σ^- in each 1.5 s beam pulse containing a total of $1.5 \times 10^6 \pi^-$. The experimental target consisted of an 8 cm long beryllium rod, located downstream of the DISC. The incident Σ were tracked in multiwire proportional chambers (MWPCs), and the charged reaction products were measured in a magnetic spectrometer equipped with MWPCs and drift chambers. Protons, kaons and pions were distinguished in two multicell threshold gas Cerenkov counters C1 and C2 which had pion thresholds of 14 GeV/c and 10 GeV/c, respectively. The cell structure of these Cerenkov counters was matched by two scintillator hodoscopes H4 and H5. The additional deflection of the second magnet SM2 was sufficient to separate positive and negative charged particles at the position of H4.

The trigger was designed to select final states of the type $(\Lambda K^- \pi^+)$ + anything, therefore at least two charged particles coming from the target were required in hodoscope H1. In addition the decay $\Lambda \rightarrow p\pi^-$ had to occur before H2, thus at least four particles were required in H2 and H3. A K^- candidate had to pass through the negative-particle region of H4 and

not to count in the corresponding cell of C1, $(\overline{C1_i} \times H4_i)$. A proton candidate had to fulfil the condition $(\overline{C2_j} \times H5_j)$ in the positive-particle region of C2. About 1.5% of the Σ^- fulfilled these trigger requirements and in a 20 day period interactions corresponding to 10^9 incident Σ^- were recorded.

In this letter only the analysis of the $(\Lambda K^- \pi^+ \pi^+)$ channel is described. Other final states, such as $(\Lambda K^- \pi^+)$ are still under study.

The Λ were identified through their $p\pi^-$ decays. The closest distance of approach between the π^- and the p tracks had to be less than 3 mm and the reconstructed decay vertex was required to be between the target and H2. The proton had to traverse the whole length of the apparatus. The $(p\pi^-)$ effective mass had to be within ± 4 MeV/c² of the Λ mass (Fig. 3a). After these cuts the background under the Λ signal was found to be less than 5%.

The identification of the K^- was made by the combined use of C1 and C2, taking into account the different thresholds of C1 and C2, the limited acceptance of C2 and problems associated with overlapping tracks³⁾. The Cerenkov 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%. To reduce further the pion contamination the additional condition $(\overline{C2_j} \times H5_j)$ was imposed for tracks with momenta below the K^- threshold of 36 GeV/c. It was not practical to select K^- below 17 GeV/c using C2 alone because of its very restricted acceptance for these low momenta. We emphasize that the kinematic cuts to the K^- candidates followed naturally from the threshold and acceptance properties of the two Cerenkov counters.

Particles which were not identified as K^- or as Λ decay products were taken to be pions. A positive Cerenkov 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.

To suppress secondary interactions and random tracks a vertex cut was applied. The tracks of the K^- and both π^+ had to intersect with the incoming Σ^- trajectory in the target region with a closest distance of approach (CDA) of less than 2 mm. The resolution perpendicular to the beam direction was 250 μm and along the beam direction a few centimetres. This did not allow us to separate production and decay vertices of charmed particles. The CDA cut was sufficiently loose that decays of particles with lifetimes of up to 10^{-11} s would not be rejected.

The $(\Lambda K^- \pi^+ \pi^+)$ effective mass distribution is shown in Fig. 2a. There is a prominent narrow peak which is contained in two bins of 15 MeV/c^2 centred at 2460 MeV/c^2 . The smooth curve in Fig. 2a shows the background under the peak obtained by fitting a polynomial of order 3 to the mass range from 2100 to 3090 MeV/c^2 excluding the two channels of the signal ($\chi^2 = 0.85/\text{DF}$). Alternative background shapes have been considered, for example those obtained by mixing Λ , K^- , π^+ from different events, or by requiring a negative charged pion in place of one of the positive ones. The background has also been estimated by taking the average of several histogram channels on both sides of the peak. All methods gave compatible results of 147 ± 5 events. Thus the signal contains 82 ± 16 events. If the peak is interpreted as a statistical fluctuation of the background, it corresponds to an effect of more than 6 standard deviations.

The absolute value of the mass scale and its linearity have been checked with reconstructed known particles and resonances in the mass range from the K^0 to the Ω^- . For the extrapolation to 2500 MeV/c^2 a systematic uncertainty of 25 MeV/c^2 has been estimated.

We have checked that the signal is not a reflection of a misidentified strangeness -1 state by assigning the π^- mass to the K^- candidate (Fig. 2b) and also by assigning the K^+ mass to one of the positive pions (Fig. 2c). In both cases no significant peak is seen. As the apparatus could not distinguish between K^- and antiprotons we have furthermore checked that the peak is not produced by a misinterpretation of an antiproton as a K^- . We conclude that the observed final state has strangeness -2 and in view of its narrow width we tentatively identify it as arising from the weak decay of the charmed strange baryon Λ^+ [quark content (csu)].

A Monte Carlo (MC) simulation of the experiment was performed which included geometrical apertures, detection and reconstruction efficiencies, interaction and decay losses, and multiple scattering. The mass resolution for Λ 's (Fig. 3a) and for other reconstructed particles are well reproduced. The calculated mass resolution for the decay $A^+(2460) \rightarrow \Lambda K^- \pi^+ \pi^+$ is 23 MeV/c² (FWHM), compatible with the observed width of the signal.

The distributions of the transverse momentum p_T and of the longitudinal momentum p_L for the A^+ , after subtraction of the background, are shown in Figs. 3c and 3d. The behaviour of the background was determined from the 5 channels on each side of the signal (Fig. 2a). The invariant cross section was parametrized as

$$E \frac{d^3\sigma}{dp^3} \propto (1-x)^n e^{-bp_T^2}, \text{ where } x = p_L^{\text{cm}}/p_{\text{max}}^{\text{cm}}$$

and MC simulations for several values for n and b were performed. From the comparison of data and MC simulations we conclude $n = 1.7 \pm 0.7$ and $b = (1.1^{+0.7}_{-0.4}) (\text{GeV}/c)^{-2}$.

The overall acceptance of the apparatus is strongly dependent on p_L (Fig. 3b). For fixed p_L the uncertainty on the shape of the p_T distribution introduces a systematic error of about 20%. Because the acceptance is very small at low values of p_L we have calculated the cross section times branching ratio ($\sigma \cdot B$) only for $p_L > 82 \text{ GeV}/c$, i.e. $x > 0.6$.

$$\sigma \cdot B = \frac{N_{A^+}}{N_{\Sigma} \cdot A_c \cdot T_{\text{eff}} \cdot R \cdot \epsilon_{\text{Tr}}} = (5.3 \pm 2.0) \mu\text{b}/\text{Be nucleus} \quad (x > 0.6)$$

where

$N_{A^+} = 60 \pm 14$ is the number of events in the signal for $x > 0.6$;

$N_{\Sigma} = (7.5 \pm 0.7) \times 10^8$ is the number of Σ^- after correction for interactions and decay before the target;

$A_c = (4.7 \pm 1.3) \times 10^{-2}$ is the overall acceptance given by MC simulation;

$T_{\text{eff}} = (6.9 \pm 0.5) \times 10^{23}$ is the number of Be atoms per unit area corrected for attenuation and secondary interactions;

$R = 0.642$ is the branching ratio for $\Lambda \rightarrow p\pi^-$;

$\varepsilon_{\text{Tr}} = 0.72 \pm 0.04$ is the trigger efficiency.

The statistical error is 23% and the systematic error is estimated to be 30%.

The observed final state has baryon number +1, charge +1, and strangeness -2. Such a state cannot be produced in the strong decay of a particle constructed from 3 quarks of the flavours up, down, and strange. Only multiquark baryons composed of at least five quarks could decay strongly into a channel with these quantum numbers. In view of the narrow width of the observed signal we therefore suggest its interpretation as the Cabibbo-favoured weak decay of the charmed strange baryon Λ_c^+ , which contains an up, a strange, and a charmed quark. The mass of this particle is expected to be approximately 200 MeV/c² above that of the Λ_c , leading to a mass of approximately 2500 MeV/c² which is compatible with the observed mass of 2460 MeV/c².

The invariant cross section is reasonably described by $(1-x)^{1.7}$ for $x > 0.6$, where this experiment was sensitive. An extrapolation into the region $x < 0.6$ has large uncertainties, as the x behaviour there is unknown. In Table 1 we give values of $\sigma \cdot B$ for $x > 0$ for two different assumptions. First we assume that the description $(1-x)^n$ is valid for the whole range, using values of n given by the experimental uncertainties (rows 1-3). Secondly we assume that the invariant cross section is constant below $x = 0.6$ and then falls off with $(1-x)^{1.7}$ (row 4). The numerical values in the table correspond to cross section per nucleon. Generally, the cross section per nucleus is given by the cross section per nucleon multiplied with a factor A^α , where A is the atomic number. As α is unknown for open charm production, we have used A^1 and $A^{2/3}$ without taking into account a possible variation of α as a function of x . The absence of a branching-ratio measurement makes it impossible to quote a value for the integrated cross section.

The Λ_c^+ contains only one valence quark in common with the incident Σ^- . The observed x dependence, $(1-x)^{1.7}$, may seem, at first sight, surprisingly small. However, one should recall that such a "leading particle

effect" is used in high-energy hyperon beams, where protons produce Σ^- and Ξ^- with measured $(1-x)^{1.5}$ and $(1-x)^3$ dependences, respectively²⁾.

For the analysis the data from more than 200 tapes were transferred from CERN to the Rutherford Appleton Laboratory via satellite. We thank the STELLA groups for their help.

REFERENCES

- 1) See, for example, F. Halzen, Rapporteur's talk, 21st Int. Conf. on High-Energy Physics, Paris, 1982, and references therein.
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Table 1

Integrated cross section times branching ratio
for $x > 0$ in μb per nucleon for different assumptions (see text).

α n	$\frac{2}{3}$	1
1.0	13.3	6.4
1.7	26.4	12.7
2.4	51.8	24.9
0 for $x \leq 0.6$ 1.7 for $x > 0.6$	9.8	4.7

Figure captions

Fig. 1 : Schematic layout of the apparatus. A, B, C, D, E, F = MWPCs; DC = drift chambers; SM1, SM2 = magnets; C1, C2 = gas Cerenkov counters; DISC = DISC Cerenkov counter; H1-H5 = scintillator hodoscopes; Σ^- = incident hyperon beam.

Fig. 2 : Effective mass distributions, points with error bars are data, lines are fits of a polynomial of the order of 3.

- a) ($\Lambda K^- \pi^+ \pi^+$) effective mass, containing 4002 combinations made from 3352 events. 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.
- b) ($\Lambda \pi^- \pi^+ \pi^+$) effective mass, where the π^- mass was assigned to the K^- for the combinations in (a).
- c) ($\Lambda K^- K^+ \pi^+$) effective mass, where the K^+ mass was assigned to one π^+ for the combinations in (a); therefore every combination of (a) gives two entries in this plot.

- Fig. 3 : a) Measured ($p\pi^-$) mass distribution. The curve was obtained from the MC simulation.
- b) Calculated acceptance for $A^+(2460) \rightarrow \Lambda K^- \pi^+ \pi^+$.
- c) Measured p_T distribution. Curves are MC results for different values of b.
- d) Measured p_L distribution. Curves are MC results for different values of n.

Fig. 1

Fig. 2

Fig. 3