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WITH CHARGES +1, 0 AND -1

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EVIDENCE FOR NARROW STATES DECAYING INTO ($\Lambda\bar{p}$ + pions)
AT 3.1 GeV/c² WITH CHARGES +1, 0 AND -1 *)

M. Bourquin³, R.M. Brown⁶, H.J. Burckhart^{4,a}, P.Extermann³,
M.Gailloud⁵, W.M. Gibson¹, J.C. Gordon⁶, P. Jacot-Guillarmod⁵,
Ph. Rosselet⁵, P. Schirato^{3,b}, H.W. Siebert⁴,
V.J. Smith¹, K.-P. Streit^{2,c} and J.J. Thresher⁶

ABSTRACT

Evidence for narrow states produced by Σ^- interactions in beryllium, and decaying into ($\Lambda\bar{p}$ + pions), has been obtained in an experiment at the CERN SPS hyperon beam. At 3.1 GeV/c², the ($\Lambda\bar{p}\pi^+\pi^+$), ($\Lambda\bar{p}\pi^+\pi^+\pi^-$) and ($\Lambda\bar{p}\pi^+\pi^-$) effective mass distributions show an excess of 45, 19 and 62 events above a background of 50, 28 and 187, respectively. The possibility that these three signals are statistical fluctuations is remote. The observed widths of the signals are compatible with the mass resolution of the apparatus, 24 MeV/c² FWHM. We have not been able to find an interpretation of the quantum numbers of the final states, which are baryon number 0, strangeness -1 and charge +1, 0 and -1.

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1 H.H. Wills Physics Laboratory, University of Bristol, UK.

2 CERN, Geneva, Switzerland.

3 Université de Genève, Switzerland.

4 Physikalisches Institut, Universität Heidelberg, Fed. Rep. Germany

5 Université de Lausanne, Switzerland.

6 Rutherford Appleton Laboratory, Chilton, Didcot, UK.

a Now at CERN, Geneva, Switzerland.

b Now at Hôpital Cantonal, Geneva, Switzerland.

c Also at Physikalisches Institut, Universität Heidelberg

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In previous publications [1–3] we have reported on the observation of the charmed strange baryon Λ^+ (quark content csu^1) and on the measurement of its lifetime, in experiment WA62 at the CERN–SPS hyperon beam. The Λ^+ were produced by Σ^- of 135 GeV/c interacting in a beryllium target, and were observed as a narrow peak at 2460 MeV/c² in the $(\Lambda K^- \pi^+ \pi^+)$ effective mass distribution. In the same sample, we have observed a narrow peak at 3.1 GeV/c² in the $(\Lambda \bar{p} \pi^+ \pi^+)$ effective mass distribution, which was obtained by assigning the $\bar{p}$ mass to the K^- candidates. This peak is the main subject of the present publication.

The experimental apparatus is shown in fig. 1. The incident Σ^- were identified by a DISC Cherenkov counter and directed onto an 8cm long beryllium target. Charged particles emerging from the target were observed in a magnetic spectrometer equipped with MWPCs and driftchambers. Two multicell Cherenkov counters C1 and C2 served to distinguish between pions and heavier particles. Their pion thresholds were 14 and 10 GeV/c, respectively. The trigger was designed to select final states of the type $(\Lambda K^- \pi^+ + \text{anything})$, therefore at least two particles were required in hodoscope H1 and at least four in both hodoscopes H2 and H3. Furthermore we required a slow negative particle (K^- candidate) and a slow positive particle (proton candidate), indicated by the absence of signals in the corresponding cells of C1 and C2 respectively. In total, 1.5×10^7 triggers produced by 10^9 incident Σ^- were recorded in a period of 20 days. More details on the apparatus and the trigger can be found in [1,3].

The Λ^+ signal was observed in a $(\Lambda K^- \pi^+ \pi^+)$ sample selected with the following criteria. Λ decaying to $p\pi^-$ were identified by the reconstructed decay vertex and the effective $(p\pi^-)$ mass, which was determined with an accuracy of 4 MeV/c² FWHM. By requiring the decay vertex to be downstream of the target and upstream of hodoscope H2, and the effective mass to be equal to the Λ mass within ± 4 MeV/c², we obtained a sample of Λ candidates with less than 5% background. As K^- candidates, we selected all negatively charged particles which came from the target, had a momentum $p > 17$ GeV/c and traversed the Cherenkov counters C1 and C2 without producing light in the corresponding cells. More than 90% of the charged particles remaining after the Λ and K^- selection did not traverse the second magnet SM2, and thus did not reach the Cherenkov counters. Therefore, we considered them all as pions.

In order to verify that the observed peak in the $(\Lambda K^- \pi^+ \pi^+)$ effective mass distribution was not a manifestation of a different state, caused by a wrong mass assignment, we reconstructed the events under various hypotheses for the masses [1]. In this analysis, we found a rather prominent peak at 3.1 GeV/c² in the $(\Lambda \bar{p} \pi^+ \pi^+)$ mass spectrum, shown by the dashed histogram in fig. 2a. The particle

¹ The Particle Data Group has recommended that this particle be renamed Ξ_c^+

combinations in this region of the $(\Lambda\bar{p}\pi^+\pi^+)$ mass distribution had no overlap with the particle combinations in the A^+ region of the $(\Lambda K^-\pi^+\pi^+)$ mass distribution.

The width of the peak at $3.1 \text{ GeV}/c^2$ was compatible with the mass resolution of the apparatus, which was $24 \text{ MeV}/c^2$ FWHM for this particle combination. In a $30 \text{ MeV}/c^2$ wide mass window centred at $3105 \text{ MeV}/c^2$, the peak contained a signal of 53 events over a background of 136 ± 5 . The background was estimated from adjacent $75 \text{ MeV}/c^2$ wide windows on each side of the signal window, assuming a linear distribution in this range.

In order to improve the $\bar{p}$ selection, we added two more selection criteria. As the K^- and $\bar{p}$ candidates had momenta below $50 \text{ GeV}/c$, the apparatus was not able to distinguish between them, and therefore we had to consider all K^- candidates also as $\bar{p}$ candidates. So far, the $K^-/\bar{p}$ candidates had been required to have momenta $p > 17 \text{ GeV}/c$. Because of their larger mass, $\bar{p}$ from decays of heavy states are expected to have larger laboratory momenta than K^- or π^- . From a Monte Carlo simulation of phase-space decays of particles with a mass of $3.1 \text{ GeV}/c^2$ into $(\Lambda\bar{p} + \text{pions})$, we found that less than a fifth of such decays would be lost by requiring the $\bar{p}$ momentum to be $> 22 \text{ GeV}/c$ instead of $> 17 \text{ GeV}/c$. In the data, however, one third of the $K^-/\bar{p}$ candidates had momenta below $22 \text{ GeV}/c$. After requiring the $\bar{p}$ momentum to be $> 22 \text{ GeV}/c$, the numbers for signal and background were $S/B = 40/84$.

With the same $\Lambda, \bar{p}$ selection criteria, we then investigated all combinations of $\Lambda, \bar{p}$ and up to three charged pions, assuming all observed particles except the $\bar{p}$ candidate and the Λ decay particles to be pions. When writing the data summary tapes, we had required at least two positively charged particles, therefore events with a reconstructed Λ decay had to contain at least one π^+ candidate. Thus we obtained six mass spectra with different total charges or pion multiplicities. At $3.1 \text{ GeV}/c^2$, we found two other peaks, one in the $(\Lambda\bar{p}\pi^+\pi^+\pi^-)$ mass distribution and one in the $(\Lambda\bar{p}\pi^+\pi^-)$ mass distribution. In the following, we will label these peaks as U^+, U^0 and U^- . The signal/background was $S/B = 20/42$ for the U^0 and $69/256$ for the U^- .

The second criterion was based on the signals observed in the scintillator hodoscope H1, which was placed 50 cm downstream of the target. It consisted of 16 radial cells and covered an approximately rectangular area of 8 cm (hor.) $\times$ 5 cm (vert.). In order to verify the extrapolation of the $\bar{p}$ track into the target, we required a signal with a pulse height between 0.8 and 2.3 times the mean pulse height of a relativistic particle, in the corresponding cell of H1. Before this cut could be applied, we had to reject all events, where the ADC information was faulty owing to an intermittent failure in the ADC readout, which was discovered only after data taking. The fraction of events showing this fault, 13%, was uniform throughout the

mass plots. These pulse-height requirements reduced the data samples by one third, changing the signal/background to $S/B = 46/52$ for the U^+ , $21/31$ for the U^0 and $70/195$ for the U^- .

There is one event contributing an entry to both the U^+ and U^0 signal windows, one event contributing to both the U^0 and U^- signal windows and seven events contributing to both the U^- and U^+ signal windows. These numbers are consistent with the observed behaviour of the background. The numbers of events contributing two entries to the same signal window are 1,2,9 for the U^+, U^0, U^- respectively, and there is one event contributing three entries to the U^0 signal window. In order to avoid multiple counting of signal events, we weighted all pairs of mass combinations which were closer than $30 \text{ MeV}/c^2$ to each other, with a factor $1/2$ and all corresponding triplets with a factor $1/3$. This correction resulted in $S/B = 45/50$ for the U^+ , $19/28$ for the U^0 and $62/187$ for the U^- . The corresponding effective mass distributions are shown in figs. 2a–2c, which contain 1727 ($\Lambda \bar{p} \pi^+ \pi^+$) combinations from 1482 events, 1052 ($\Lambda \bar{p} \pi^+ \pi^+ \pi^-$) combinations from 751 events and 6182 ($\Lambda \bar{p} \pi^+ \pi^-$) combinations from 4465 events.

The above numbers for signal and background were obtained with signal windows centred at 3105, 3095 and 3115 MeV/c^2 for the U^+, U^0 and U^- , respectively. The peak centres coincide with the signal window centres within the statistical uncertainty of $\pm 5 \text{ MeV}/c^2$. The systematic uncertainties on the mass differences between the different decay channels involved are a few MeV/c^2 , and the mass scale has an overall systematic uncertainty of $\pm 20 \text{ MeV}/c^2$. The intrinsic widths are $\Gamma < 30 \text{ MeV}/c^2$ (90% CL) for the U^+ and U^0 , and $\Gamma < 80 \text{ MeV}/c^2$ (90% CL) for the U^- . We also note a similar peak in the ($\Lambda \bar{p} \pi^+ \pi^+ \pi^-$) mass distribution at 3410 MeV/c^2 (fig. 2b), with $S/B = 26/30$.

The distributions of the reconstructed Λ masses show the same shape for the events in the signal windows as for the total Λ sample. We have checked that the U peaks are not manifestations of other states, by assigning all possible combinations of the π , K and p masses to the $\bar{p}$ and π candidates. The events contributing to the observed U peaks are distributed over much wider mass ranges under all other mass hypotheses. We have also checked that the observed signals are not concentrated in special run periods or in limited regions of the apparatus.

We have calculated the probabilities for obtaining peaks like the observed U peaks from statistical fluctuations. Usually, the significance of peaks appearing over a smooth background is parametrized by the ratio S/Δ , where S denotes the excess of events and Δ the estimate of the statistical fluctuation of the background. Frequently, one sets $\Delta^2 = B + (\Delta B)^2$, where B is the estimate of the background under the peak and ΔB the uncertainty of this estimate. Clearly, the significance of a peak increases with this ratio. Quantitatively, the significance should be described by the

probability for a fluctuation producing a peak with the same or larger S/Δ . We have determined this probability for the U^+ peak by a Monte Carlo calculation, using Poisson statistics to simulate the fluctuations in $2.5 \text{ MeV}/c^2$ mass bins. The expectation values of the Poisson distributions were given by a smooth distribution with the same shape and total event number as the observed $(\Delta\bar{p}\pi^+\pi^+)$ mass distribution between 2600 and 3400 MeV/c^2 (see fig. 2a). Signal S and background B were evaluated in the same way as described above for the data, and no constraint was placed on the position of the peak in the mass spectrum. The result was a probability of 6×10^{-5} for obtaining the U^+ peak through statistical fluctuations.

Analogous calculations for the U^0 peak and the U^- peak yielded the probabilities 0.2 and 0.009, respectively. If the centres of the spurious peaks are constrained to be within $\pm 10 \text{ MeV}/c^2$ of a fixed mass, the probabilities are 9×10^{-3} and 4×10^{-4} . The probability for finding two additional spurious peaks as significant as the observed U^0 and U^- peaks, with masses within $\pm 10 \text{ MeV}/c^2$ of the U^+ mass, is given by the product of the corresponding probabilities and the number of pairs of additional spectra (in total 10). The resulting number is 4×10^{-5} , and thus the total probability for fluctuations simulating the observed U^+ , U^0 and U^- peaks is very small.

We have determined upper limits on the U lifetimes from the distributions of the U decay vertices, reconstructed from the $\bar{p}$ and pion tracks. From a comparison of these distributions for the signal and background mass windows, we obtained $\tau < 2 \times 10^{-12} \text{ s}$ (90% CL) for all three U states. We have also reconstructed, wherever possible, the Σ^- interaction vertex from the track of the incident Σ^- and tracks emerging from the target and not belonging to the U [2]. The distributions of the distance between the interaction vertex and the U decay vertex provided tighter limits on the lifetimes, but the reconstruction requirements (see ref. 2 for details) reduced the samples to $S/B = 30/29$ for the U^+ , $8/14$ for the U^0 and $48/93$ for the U^- . The statistics of the U^0 sample were too small for an improvement on the upper limit quoted above, but for both the U^+ and U^- we obtained $\tau < 5 \times 10^{-13} \text{ s}$ (90% CL).

The momentum spectrum of the U^+ events, after subtraction of background, is shown in fig. 3a, while fig. 3b shows the distribution of p_t , the U^+ momentum transverse to the beam. There is no significant difference between signal and background in these spectra. In order to determine the x_F and p_t dependence of the production cross-section, we made a Monte Carlo calculation of these distributions, assuming a four-body phase-space decay and a production cross-section of the form

$$E \cdot d^3\sigma/dp^3 \propto (1 - x_F)^n \cdot \exp(-b \cdot p_t^2)$$

The resulting distributions are shown as curves in fig. 3. By fitting the Monte Carlo distributions to the data, we obtained

$$n = 2.1 \pm 0.6 \text{ and } b = (1.4 \pm 0.5) (\text{GeV}/c)^{-2} \text{ for the } U^+,$$

$$n = 1.0 \pm 0.5 \text{ and } b = (1.8 \pm 1.0) (\text{GeV}/c)^{-2} \text{ for the } U^0,$$

$$n = 1.3 \pm 0.8 \text{ and } b = (2.5 \pm 1.1) (\text{GeV}/c)^{-2} \text{ for the } U^-.$$

The quoted uncertainties are statistical only. These values of n are typical for a leading particle effect, as observed for example in inclusive K^+ production by protons, where $n \approx 2$. For K^- production by protons, $n \approx 5$ has been measured. This difference can be explained by the fact that only the K^+ has a valence quark in common with the incident proton [4]. The values of n measured in this experiment might indicate that the observed final states contain the strange quark of the incident Σ^- .

We have determined the product of cross-section and branching ratio in the kinematic region where the apparatus was sensitive, $p_t < 1 \text{ GeV}/c$ and $0.6 < x_F < 1$, which corresponds to laboratory momenta $p_U > 82 \text{ GeV}/c$. For this calculation, we assumed an intrinsic width $\Gamma = 0$ and phase-space decay. The result was

$$\sigma \cdot B = (4.8 \pm 1.4 \pm 0.8) \mu\text{b}/\text{Be nucleus for the } U^+,$$

$$\sigma \cdot B = (1.2 \pm 0.7 \pm 0.2) \mu\text{b}/\text{Be nucleus for the } U^0,$$

$$\sigma \cdot B = (3.0 \pm 1.7 \pm 0.5) \mu\text{b}/\text{Be nucleus for the } U^-.$$

The first error in each line is the statistical error on the number of events including the uncertainties from the background estimate. The second error is systematic and is dominated by the uncertainties on the number of Σ^- decaying inside or downstream of the DISC counter and by the effects of secondary interactions in the target.

What is the nature of the U ? The fact that the three peaks have the same mass within a few MeV/c^2 and are observed with similar rates, suggests that they represent the same basic object with different charges.

The observed masses are compatible with the J/ψ mass, but the quantum numbers of the three U states are not those of charmonium. If the observed final states are the result of strong decays, then the U^+ , with the exotic combination of baryon number 0, charge +1 and strangeness -1, must contain at least four quarks, namely $s\bar{u}d\bar{d}$. (The minimal quark configuration for the U^0 and U^- would be $s\bar{d}$ and $s\bar{u}$, respectively). It would be surprising, however, if a multiquark state at $3.1 \text{ GeV}/c^2$, containing only light quarks, were to have a width $\Gamma < 30 \text{ MeV}/c^2$.

The quark configuration $s\bar{u}d\bar{d}$ could in principle come from a weak decay $c \rightarrow s\bar{u}d\bar{d}$, so that the U^+ would be a D^{*+} . But a D^{*+} would presumably decay by the strong interaction to $D + \text{pions}$. Also, the U^- would not fit into this scheme, unless it is a multiquark state with charm.

To summarize, we have observed evidence for three narrow states at 3.1 GeV/c², decaying into ($\Lambda\bar{p}$ + pions). We have not been able to find an interpretation of these states in terms of known or expected phenomena, therefore verification of this observation is highly desirable.

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Figure captions

Fig. 1) Schematic layout of the apparatus.

A,B,C,D,E,F = clusters of MWPCs; DC = clusters of driftchambers;
SM1 and SM2 = bending magnets; C1 and C2 = gas Cherenkov counters;
H1 – H5 = scintillator hodoscopes; Σ^- = incident hyperon beam.

Fig. 2) Effective mass distributions.

The dashed histogram in a) shows the initial sample.

The straight lines represent the background estimates given in the text.

A vertical line on the figure corresponds to the same mass value in all three plots, however the bin limits do not coincide.

Fig. 3) a) Momentum distribution for U^+ .

Histogram: data; curve: Monte Carlo calculations for different values of n .

b) Transverse momentum distribution for U^+ .

Histogram: data; curve: Monte Carlo calculations for different values of b .

Fig. 1

Fig. 2

Fig. 3