Evidence for an Excited Hyperon State in $pp \to pK^+Y^{0*}$

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Indications for the production of a neutral excited hyperon in the reaction $pp \to pK^+Y^{0*}$ are observed in an experiment performed with the ANKE spectrometer at COSY-Jülich at $p_{\text{beam}} = 3.65\ \text{GeV}/c$. Two final states were investigated simultaneously, viz. $Y^{0*} \to \pi^+X^-$ and π^-X^+, and consistent results were obtained in spite of the quite different experimental conditions. The parameters of the hyperon state are $M(Y^{0*}) = (1480 \pm 15)\ \text{MeV}/c^2$ and $\Gamma(Y^{0*}) = (60 \pm 15)\ \text{MeV}/c^2$. The production cross section for Y^{0*} decaying through these channels is of the order of few hundred nanobarns. Since the isospin of the Y^{0*} has not been determined here, it could either be an observation of the $\Sigma(1480)$, a one-star resonance of the Particle Data Group tables, or, alternatively, a Λ hyperon. Relativistic quark models for the baryon spectrum do not predict any excited hyperon in this mass range and so the Y^{0*} may be of exotic nature.

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The question of how hadrons arise from QCD is central to a fundamental understanding of hadronic multiquark and gluon systems. There has been a recent renaissance of QCD spectroscopy, triggered by observations of new narrow resonances, enhancements near thresholds, and possibly exotic states. Taken in conjunction with lattice QCD, which is poised to provide the theoretical insight into strong QCD, the new data may pave the way to achieve this understanding.

The production of hyperons and their decay properties have been a focus of experimental investigations ever since their discovery, mostly in hadron-induced reactions, but recently also in photoproduction. In comparison to the excitation spectrum of the nucleon resonances (N, Δ), the excited states of hyperons (Λ, Σ) are still much less well known. The nature of experimentally well established states, such as the $\Lambda(1405)$, is not at all understood yet. This hyperon may be a genuine three-quark system, a molecularlike meson-baryon bound state, or even of exotic type.

The $\Sigma(1480)$ hyperon is far from being an established resonance. In the most recent compilation of the Particle Data Group [1], it is described as a "bump," with unknown quantum numbers and given a mere one-star rating. Very recently ZEUS has reported indications for a structure in the invariant mass spectrum for K_S^0p and $K_S^0\bar{p}$, which may correspond to the $\Sigma(1480)$ [2]. However, the structure appears on a steeply varying background and therefore its significance is difficult to estimate. The Crystal Ball investigation of the $K^-p \to \pi^0\pi^0\Lambda$ reaction showed no sign for the resonance in the $\pi^0\Lambda$ invariant mass spectra, but it should be noted that these are dominated by the $\Sigma^0(1385)$ [3].

In view of this uncertainty, we have investigated whether additional information might be obtained from proton-proton interactions at low energies. In so doing, we have found evidence for a neutral hyperon resonance Y^{0*} in data originally taken for scalar meson production studies [4,5].

The experiments have been performed at the Cooler Synchrotron COSY, a medium energy accelerator and storage ring for protons and deuterons, which is operated at the Research Center Jülich (Germany) [6]. COSY supplied stored proton beams with a momentum of $3.65\ \text{GeV}/c$ at a revolution frequency of $\sim 10^6\ \text{s}^{-1}$. Using a hydrogen cluster-jet target (areal density $\sim 5 \times 10^{14}\ \text{cm}^{-2}$) the average luminosity during the measurements was $L = (1.38 \pm 0.15) \times 10^{31}\ \text{s}^{-1}\,\text{cm}^{-2}$.

The ANKE spectrometer [7] used in the experiments consists of three dipole magnets, which guide the circulating COSY beam through a chicane. The central C-shaped spectrometer dipole D2, placed downstream of the target, separates the reaction products from the beam. The ANKE detection system, comprising range telescopes, scintillation counters and multiwire proportional chambers, simultaneously registers particles of either charge and measures their momenta [8].

A multibody final state, containing a proton, a positively charged kaon, and a charged pion, together with an unidentified residue X, was studied in the $pp \to pK^+\pi^\pm X^\mp$ reaction. Positively charged kaons and pions could be measured in the momentum ranges 0.2–0.6 GeV/c and 0.2–0.9 GeV/c, respectively, negative pions between 0.4 and 1.0 GeV/c, and protons from 0.75 GeV/c up to the kinematic limit. The angular acceptance of D2 is $|\vartheta_{\text{H}}| \lesssim 12°$ horizontally and $|\vartheta_{\text{V}}| \lesssim 5°$ vertically for any ejectile. By measuring delayed signals from the decay of stopped kaons, K^+ mesons can be identified in a background of pions, protons, and scattered particles up to 10^6 times more intense.

Events with three identified charged particles ($p, K^+, \pi^\pm$) were retained for further analysis. In Fig. 1 the missing-mass distributions $MM(pK^+\pi)$ vs $MM(pK^+)$ are shown for the reaction channels $pp \to pK^+\pi^+X^-$ and $pp \to pK^+\pi^-X^+$. The triangular shape of the distributions is due to the combination of kinematics and ANKE acceptance. Since the probability for detecting three-particle coincidences ($pK^+\pi^+$) is about an order of magnitude smaller than for ($pK^+\pi^-$), the resulting numbers of events are also drastically different.

For the reaction $pp \to pK^+\pi^+X^-$ a clear enhancement, corresponding to $X^- = \Sigma^-(1197)$, is observed on a top of a low background (see projection of the upper part of Fig. 1 in the upper part of Fig. 2). In the charge-mirrored $pp \to pK^+\pi^-X^+$ case, the π^- may originate from different sources, e.g., a reaction with $X^+ = \Sigma^+(1189)$ or a secondary decay of $\Lambda \to p\pi^-$, arising from the major background reaction $pp \to pK^+\Lambda \to pK^+\pi^-p$. Protons from the latter reaction have been rejected by cutting $MM(pK^+\pi^-)$ around the proton mass (lower part in Fig. 1). Nevertheless the missing-mass distribution for the (π^-X^+)-final state is more complicated and the $\Sigma^+(1189)$ band is almost hidden underneath a strong background of, e.g., π^0p, $\pi^0\gamma p$, π^+n arising from the decay of heavier hyperons (see lower part of Fig. 2). For both final states, background due to misidentified particles of different type is experimentally estimated to be $<3\%$.

For further event selection, different cuts have been applied for the two final states: for (π^+X^-) the Σ^- has been selected (1175 and 1220 MeV/c^2), while for (π^-X^+) the corresponding range is between 1175 and 1300 MeV/c^2 in order to include Σ^+ as well as Σ^- with a π^- in its decay.

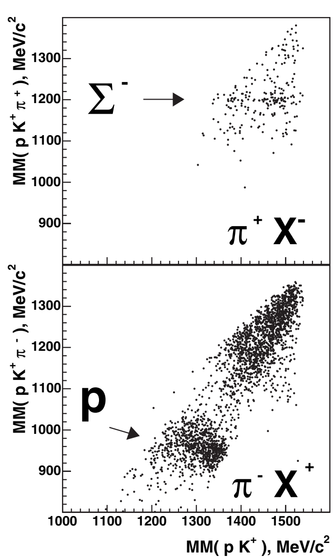

FIG. 1. Missing-mass $MM(pK^+\pi)$ vs $MM(pK^+)$ distributions for π^+ (upper) and π^- (lower) obtained in the reaction $pp \to pK^+\pi^\pm X^\mp$.

This cut largely excludes neutral hyperons producing a final state with two protons. The missing-mass distributions $MM(pK^+)$ for such events are plotted in Fig. 3(a). For π^+X^-, a double-humped structure is observed, with peaks around 1390 MeV/c^2 and 1480 MeV/c^2 (upper left). In the π^-X^+ case, the distribution also peaks at 1480 MeV/c^2 (upper right). The different shapes and event numbers of the resulting spectra are due to the various sources of π^+ and π^- (see above). An obvious question is whether these distributions can be explained by the production of well established hyperon resonances [$\Sigma(1385)$, $\Lambda(1405)$, and $\Lambda(1520)$] plus nonresonant contributions or whether an additional source needs to be invoked, e.g., $pp \to pK^+Y^{0*}$ with a further Y^{0*} hyperon state.

In order to try to answer this question, Monte Carlo simulations have been performed for both final states, using a simulation package based on GEANT3 [9]. The following reactions with ($pK^+\pi^\pm$) in the final state have been used as input for this, assuming phase-space distributions and applying any constraints due to isospin invariance:

(i) intermediate hyperon resonance production [1]

$$\begin{aligned} pp \to pK^+\Sigma(1385) &\to pK^+\pi^0(\pi^-p) \\ &\to pK^+\pi^\pm(\pi^\mp n) \\ &\to pK^+\pi^-(\pi^0p), \end{aligned}$$

$$\begin{aligned} pp \to pK^+\Lambda(1405) &\to pK^+\pi^0(\pi^-p)\gamma \\ &\to pK^+\pi^\pm(\pi^\mp n) \\ &\to pK^+\pi^-(\pi^0p), \end{aligned}$$

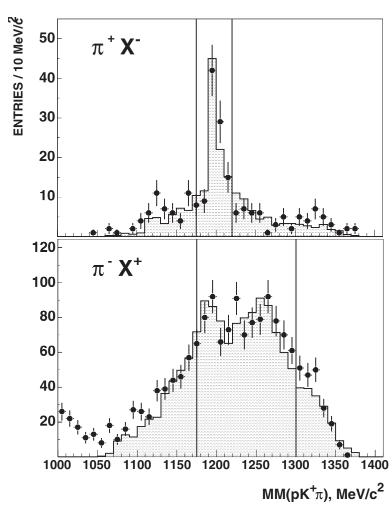

FIG. 2. Projections of Fig. 1 onto the three-particle missing mass $MM(pK^+\pi^\pm)$. Vertical lines show the Σ bands used for event selection. The results of simulations for $MM(pK^+\pi^\pm) >$ 1050 MeV/c^2, described in the text, are shown as a filled histogram.

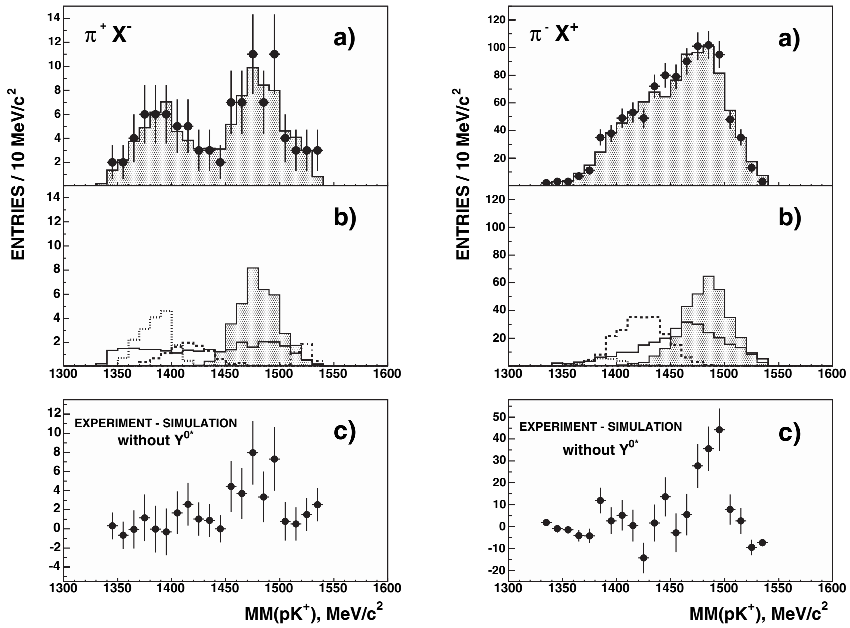

FIG. 3. Missing-mass $MM(pK^+)$ spectra for the reaction $pp \to pK^+\pi^+X^-$ (left) and $pp \to pK^+\pi^-X^+$ (right). (a) Experimental points with statistical errors are compared to the shaded histograms of the fitted overall Monte Carlo simulations; (b) The simulation includes contributions from (i) resonances [$\Sigma(1385)$ (dotted), $\Lambda(1405)$ (dashed), $\Lambda(1520)$ (dotted-dashed)], (ii) nonresonant phase-space production (solid), and (iii) the Y^{0*} resonance (shaded histogram), as described in the text; (c) Difference between the measured spectra and the sum of contributions (i) + (ii) fitted *without* Y^{0*} production. Note that the contributions of the individual partial channels are different for (b) and (c).

$$\begin{aligned} pp \to pK^+\Lambda(1520) &\to pK^+p(\pi^+\pi^-\pi^-) \\ &\to pK^+p(\pi^-\pi^0\pi^0) \\ &\to pK^+n(\pi^+\pi^-) \\ &\to pK^+\pi^0(\pi^-p)\gamma \\ &\to pK^+\pi^+\pi^-(\pi^-p) \\ &\to pK^+\pi^+\pi^-(\pi^0n) \\ &\to pK^+\pi^\pm(\pi^\mp n) \\ &\to pK^+\pi^-(\pi^0p), \end{aligned}$$

(ii) nonresonant production

$$pp \to NK^+X,$$

$$pp \to NK^+\pi X,$$

$$pp \to NK^+\pi\pi X,$$

with constraints for the relative contributions obtained on the basis of measured cross sections and phase-space considerations in the nonresonant cases [10,11].

The final state of (πN) results from the decay of ground-state hyperons, while (2π) and (3π) are from K^0 and K^- decays, respectively. X represents any known Λ or Σ hyperon which could be produced in the experiment. When there are two particles of the same kind, both are further processed as in the analysis of experimental data.

In the lower parts of Fig. 3, the difference between the measured missing-mass distributions and the sum of fitted resonant and nonresonant production—contributions listed under (i) and (ii)—is shown. For both final states (π^+X^- and π^-X^+) the shape of the measured distributions cannot be reproduced by the simulations and an excess of events is observed around the missing mass of 1480 MeV/c^2 in both cases. It is therefore suggested that another excited hyperon is produced and observed through the decay $pp \to pK^+Y^{0*} \to pK^+\pi^\pm X^\mp$.

The Y^{0*} mass and width have been determined from a fit based on simulations that cover the range from 1460 to 1490 MeV/c^2 and from 45 to 75 MeV/c^2, respectively, both in steps of 5 MeV/c^2. From a minimization procedure the following parameters of the Y^{0*}, consistent for both final states, are obtained: $M(Y^{0*}) = (1480 \pm 15)\mathrm{MeV}/c^2$ and $\Gamma(Y^{0*}) = (60 \pm 15)\mathrm{MeV}/c^2$. Note that the experimental mass resolution is of the order of 10 MeV/c^2.

The fits to the data are shown in the two parts of Fig. 3(a), while the individual contributions are plotted in Fig. 3(b). These contributions are also used to obtain the three-particle missing-mass spectra for $MM(pK^+\pi^\pm) > 1050\ \mathrm{MeV}/c^2$ as shown in Fig. 2: in comparison with the experimental results a good agreement is achieved.

The numbers of events in the two peaks are $S(Y^{0*} \to \pi^+X^-) = 35 \pm 10$ and $S(Y^{0*} \to \pi^-X^+) = 330 \pm 60$. The statistical significance of the signal, assuming that this is due to the production of the Y^{0*}, is at least 4.5 standard deviations.

In order to estimate the production cross section for Y^{0*} decaying through these channels, we used an overall detection efficiency of $\sim$7% and an integrated luminosity of $\sim$6 pb^{-1}. With acceptances obtained from simulations presented above, we arrive at cross section values of $(450 \pm 150 \pm 150)$ nb for $(\pi^+ X^-)$ and $(1200 \pm 250 \pm 500)$ nb for $(\pi^- X^+)$. The first error is statistical, while the second represents the systematic uncertainty. It can thus be concluded that the cross section estimates are consistent for both final states and are of the order of few hundred nanobarns.

Assuming that the $Y^{0*}(1480)$ hyperon exists, we briefly address the question of its possible theoretical description. In the constituent quark model, baryons are interpreted as bound states of three valence quarks where hyperons contain at least one strange quark. The baryon spectrum has been investigated systematically in a relativistic quark model with instanton-induced quark forces. No excited Λ or Σ resonances, in addition to the well known states, have been found for masses below $\approx$1600 MeV/c^2 [12]. These findings are in agreement with results obtained in the relativized quark model of Capstick and Isgur [13]. Thus, it seems to be difficult to reconcile the low mass of the Y^{0*} within the existing classification of $3q$ baryons.

In early papers, configurations of four quarks and an antiquark have been discussed for this mass range. Högaasen and Sorba have performed a group-theoretical classification of such states and arrived at an estimate of 1440 MeV/c^2 for the mass of an exotic Σ [14]. Azimov *et al.* introduced a flavor octet and an antidecuplet of exotic baryons [15,16]. For the octet, a Σ state with a mass of 1480 MeV/c^2 and a Λ state at 1330 MeV/c^2 have been suggested in Ref. [16]. There were also attempts to mix octet and antidecuplet states, based on diquark correlations, as proposed by Jaffe and Wilczek [17]. A Σ resonance with a mass of 1495 MeV/c^2 has been predicted as a member of the mixed multiplet [18].

In models, which couple nucleons with kaons and pions, quasibound states are generated with relatively low masses. In Ref. [19], a pole with the quantum numbers of the Σ, which might be identified with the $\Sigma(1480)$, is found at a mass of 1446 MeV/c^2, though a width of 343 MeV/c^2 is much larger.

Since a clear theoretical picture has not yet appeared, any conclusion about the nature of the Y^{0*} would be premature.

In summary, we have observed indications in proton-proton collisions at 3.65 GeV/c for a neutral hyperon resonance Y^{0*} decaying into $\pi^+ X^-$ and $\pi^- X^+$ final states. Its parameters are $M(Y^{0*}) = (1480 \pm 15)$ MeV/c^2 and $\Gamma(Y^{0*}) = (60 \pm 15)$ MeV/c^2, though, since it is neutral, it can be either a Λ or Σ hyperon. The production cross section is of the order of few hundred nanobarns. On the basis of existing data we cannot decide whether it is a three-quark baryon or an exotic state, although some preference towards its exotic nature may be deduced from theoretical considerations.

Further studies are required to confirm the existence of the $Y^{0*}(1480)$ hyperon and to determine its quantum numbers. Such measurements, in particular, for Y^* decays with photons in the final state, are foreseen with the WASA detector at COSY [20]. Searches for the charged Y^{-*} hyperon in the reaction $pn \to pK^+Y^{-*} \to pK^+\pi^-X^0$, using a deuterium cluster-jet target and spectator proton tagging, are also conceivable.

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[1] S. Eidelman *et al.*, Phys. Lett. B **592**, 1 (2004).
[2] S. Chekanov *et al.*, Phys. Lett. B **591**, 7 (2004).
[3] S. Prakhov *et al.*, Phys. Rev. C **69**, 042202(R) (2004).
[4] M. Büscher, Acta Phys. Pol. B **35**, 1055 (2004).
[5] V. Kleber, Int. J. Mod. Phys. A **20**, 273 (2005).
[6] R. Maier, Nucl. Instrum. Methods Phys. Res., Sect. A **390**, 1 (1997).
[7] S. Barsov *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 364 (2001).
[8] M. Büscher *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **481**, 378 (2002).
[9] I. Zychor, Acta Phys. Pol. B **33**, 521 (2002).
[10] A. Baldini *et al.*, in *Numerical Data and Functional Relationships in Science and Technology, Total Cross-Sections for Reactions of High Energy Particles*, edited by H. Schopper, Landolt-Bornstein, New Series, Group 1, Vol. 12 (Springer-Verlag, Berlin, Heidelberg, 1988).
[11] E. Byckling and K. Kajantie, *Particle Kinematics* (John Wiley & Sons Ltd., New York, 1973).
[12] U. Löhring *et al.*, Eur. Phys. J. A **10**, 447 (2001).
[13] S. Capstick and N. Isgur, Phys. Rev. D **34**, 2809 (1986); S. Capstick and W. Roberts, Prog. Part. Nucl. Phys. **45**, S241 (2000).
[14] H. Högaasen and P. Sorba, Nucl. Phys. **B145**, 119 (1978).
[15] Ya. I. Azimov, Phys. Lett. B **32**, 499 (1970).
[16] Ya. I. Azimov *et al.*, Phys. Rev. C **68**, 045204 (2003).
[17] R. Jaffe and F. Wilczek, Phys. Rev. D **69**, 114017 (2004).
[18] Y. Oh, H. Kim, and S. H. Lee, Phys. Rev. D **69**, 094009 (2004).
[19] C. Garcia-Recio, M. F. M. Lutz, and J. Nieves, Phys. Lett. B **582**, 49 (2004).
[20] H. H. Adam *et al.* (WASA-at-COSY Collaboration), nucl-ex/0411038.