Evidence for an Exotic $S = -2$, $Q = -2$ Baryon Resonance in Proton-Proton Collisions at the CERN SPS

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(Received 8 October 2003; published 29 January 2004)

Results of resonance searches in the $\Xi^-\pi^-$, $\Xi^-\pi^+$, $\overline{\Xi}^+\pi^-$, and $\overline{\Xi}^+\pi^+$ invariant mass spectra in proton-proton collisions at $\sqrt{s} = 17.2$ GeV are presented. Evidence is shown for the existence of a narrow $\Xi^-\pi^-$ baryon resonance with mass of 1.862 ± 0.002 GeV$/c^2$ and width below the detector resolution of about 0.018 GeV$/c^2$. The significance is estimated to be above 4.2σ. This state is a candidate for the hypothetical exotic $\Xi^{--}_{3/2}$ baryon with $S = -2$, $I = \frac{3}{2}$, and a quark content of $(dsds\bar{u})$. At the same mass, a peak is observed in the $\Xi^-\pi^+$ spectrum which is a candidate for the $\Xi^0_{3/2}$ member of this isospin quartet with a quark content of $(dsus\bar{d})$. The corresponding antibaryon spectra also show enhancements at the same invariant mass.

DOI: 10.1103/PhysRevLett.92.042003 PACS numbers: 14.20.Jn, 12.39.–x, 13.75.Cs

Recent experimental evidence for the first manifestly exotic baryon state opens a new chapter in spectroscopy and may help to elucidate the strong interaction in the strong coupling regime. A resonance state was observed [1–4] in the nK^+ and pK^0_s invariant mass spectra near 1.540 GeV$/c^2$ with a width smaller than the experimental resolution of 0.009 GeV$/c^2$. This strangeness $S = +1$ baryon has been identified as a candidate for the pentaquark state Θ^+ with quark content $(udud\bar{s})$.

Pentaquark states have been theoretically investigated for a long time in the context of the constituent quark model [5–8]. Some of these are expected to have charge and strangeness quantum number combinations that cannot exist for three-quark states. Using the chiral soliton model, an antidecouplet of baryons was predicted by Manohar [9] and Chemtob [10]. The lightest member was estimated by Praszalowicz [11] to lie at a mass of 1.530 GeV/c^2. Diakonov *et al.* [12] subsequently derived for this exotic baryon resonance with $S = +1$, $J^P = \frac{1}{2}^+$ a width of less than 0.015 GeV/c^2. The mass and width of the experimentally observed Θ^+ are close to the theoretical values. The authors further made predictions for the heavier members of the antidecouplet, with the isospin quartet of $S = -2$ baryons having a mass of about 2.070 GeV/c^2 and partial decay width into $\Xi\pi$ of about 0.040 GeV/c^2. This isospin $\frac{3}{2}$ multiplet contains two $\Xi_{3/2}$ with ordinary charge assignments ($\Xi^0_{3/2}$, $\Xi^-_{3/2}$) in addition to the exotic states $\Xi^+_{3/2}(uuss\bar{d})$ and $\Xi^{--}_{3/2}(ddss\bar{u})$. Walliser and Kopeliovich [13] took into account mixing with higher $\mathrm{SU}(3)_f$ multiplets and obtained a mass of 1.790 GeV/c^2 for the $\Xi_{3/2}$ isospin quartet. Jaffe and Wilczek [14], on the other hand, base their predictions on the strong color-spin correlation force and suggest that the $\Theta^+(1540)$ baryon is a bound state of two highly correlated *ud* pairs and an antiquark. In their model, the $\Theta^+(1540)$ has positive parity and lies in an almost ideally mixed $\overline{10}_f \oplus 8_f$ multiplet of $\mathrm{SU}(3)_f$. For the isospin $\frac{3}{2}$ multiplet of Ξs they predict a mass around 1.750 GeV/c^2 and a width 50% greater than that of the $\Theta^+(1540)$. This Letter presents the first experimental evidence for the existence of the exotic $\Xi^{--}_{3/2}$ member of the Ξ multiplet.

Experiments reporting the Θ^+ were conducted at energies close to its production threshold. This Letter presents the results of a search for the $\Xi^{--}_{3/2}$ and $\Xi^0_{3/2}$ states and their antiparticles in proton-proton collisions at $\sqrt{s} = 17.2$ GeV. The pK^0_s decay channel of the Θ^+ baryon is under investigation. However, the combinatorial background is larger than for the $\Xi_{3/2}$ resonances, and no significant signal has been observed yet.

Events were recorded at the CERN SPS accelerator complex with the NA49 fixed target large acceptance hadron detector [15]. The NA49 tracking system consists of four large volume (50 m^3) time projection chambers (TPCs). Two of the TPCs (VTPC1 and VTPC2) are placed inside superconducting dipole magnets. Downstream of the magnets two larger TPCs (MTPC-R and MTPC-L) provide acceptance at high momenta.

The interactions were produced with a beam of 158 GeV/c protons on a cylindrical liquid hydrogen target of 20 cm length and 2 cm transverse diameter. The trigger used beam counters in front of the target, together with an anticoincidence counter further downstream. The measured trigger cross section was 28.2 mb of which 1 mb was estimated to be elastic scattering. Thus the detector was sensitive to most of the inelastic cross section of 31.8 mb [16].

The data sample consists of about 6.5×10^6 events. Reconstruction started with pattern recognition, momentum fitting, and finally formation of global track candidates (spanning multiple TPCs) of charged particles produced in the primary interaction and at secondary vertices. For each event the primary vertex was determined. Events in which no primary vertex was found were rejected. To remove nontarget interactions the reconstructed primary vertex had to lie within ± 9 cm in the longitudinal (z) and within ± 1 cm in the transverse (x, y) direction from the center of the target. These cuts reduced the data sample to 3.75×10^6 events.

Particle identification was accomplished via measurement of the specific energy loss (dE/dx) in the TPCs. After careful calibration the achieved resolution is 3%–6% depending on the reconstructed track length [15,17]. The dependence of the measured dE/dx on velocity was fitted to a Bethe-Bloch type parametrization.

The first step in the analysis was the search for Λ candidates, which were then combined with the π^- to form the Ξ^- candidates. Next the $\Xi^{--}_{3/2}(\Xi^0_{3/2})$ were searched for in the $\Xi^-\pi^-(\Xi^-\pi^+)$ invariant mass spectrum, where the $\pi^-(\pi^+)$ are primary vertex tracks. An analogous procedure was followed for the antiparticles.

The protons and pions were selected by requiring their dE/dx to be within 3σ around the nominal Bethe-Bloch value. The Λ candidates were identified [18] by locating the vertices from neutral decays (so-called V0s, mostly upstream of VTPC1). To achieve this, the protons were paired with π^- and both tracked backwards through the magnetic field. The V0 was constrained to lie on the track with more VTPC points. A four-parameter χ^2 fit was performed to find the V0 position along the longer track and the three momentum components of the other track at this point. The resulting $p\pi^-$ invariant mass spectrum is shown in Fig. 1(a).

To find the Ξ^-, the Λ candidates with a reconstructed invariant mass within ± 0.015 GeV/c^2 around the nominal mass [shaded area in Fig. 1(a)] were combined with all π^-. The fitting procedure was the same as for the V0 finding, but in this case the track parameters of the π^- from the Ξ^- decay were varied. Several cuts were imposed to increase the significance of the Ξ^- signal. As the combinatorial background is concentrated close to the primary vertex, a distance cut of > 12 cm between the primary and the Ξ^- vertices was applied. Additional cuts on extrapolated track impact positions in the x (magnetic bending) and y (nonbending) directions (b_x and b_y) at the main vertex were imposed. To ensure that the Ξ^- originates from the main vertex its $|b_x|$ and $|b_y|$ had to be less than 2 and 1 cm, respectively. On the other hand, the π^- from the Ξ^- decay had to have $|b_y| > 0.5$ cm. The resulting $\Lambda\pi^-$ invariant mass spectrum is shown in Fig. 1(b), where the Ξ^- peak is clearly visible. The Ξ^- candidates were selected within ± 0.015 GeV/c^2 of the nominal Ξ^- mass. Only events with one Ξ^- candidate (95%) were

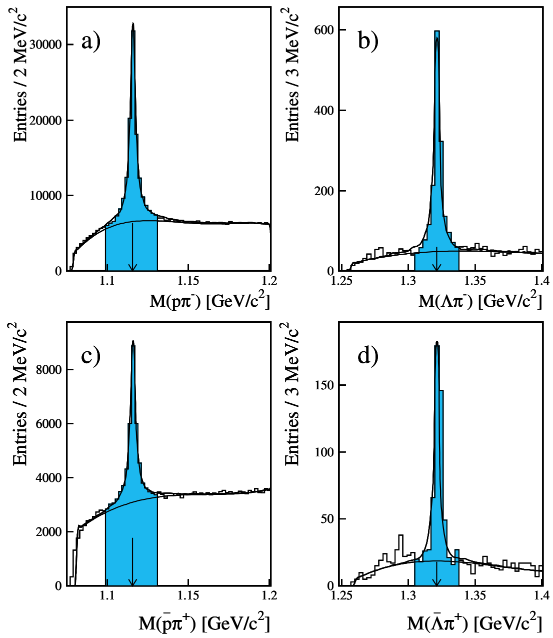

FIG. 1 (color online). (a) The $p\pi^-$ invariant mass spectrum for V0 topologies. (b) The $\Lambda\pi^-$ invariant mass spectrum for Ξ^- candidates. Curves depict the results from a simulation of the detector response, and shaded areas indicate the range of the selected candidates. The arrows show the nominal Λ and Ξ masses. (c),(d) Analogous spectra for $\overline{\Lambda}$ and $\overline{\Xi}^+$.

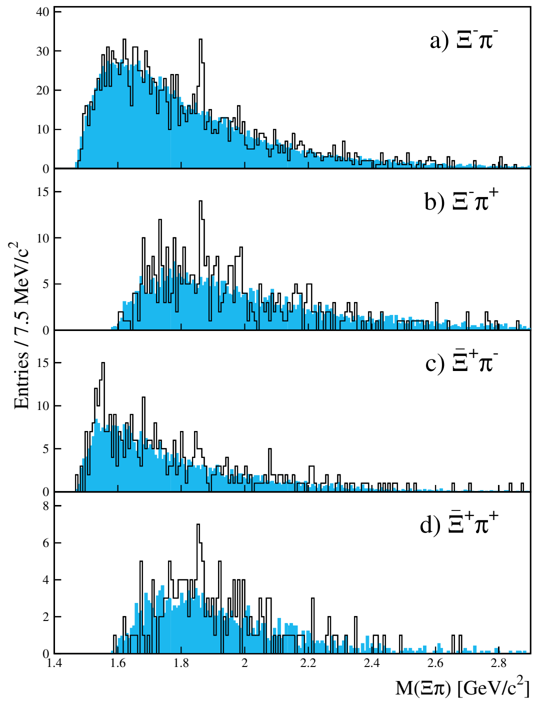

FIG. 2 (color online). Invariant mass spectra after selection cuts for $\Xi^-\pi^-$ (a), $\Xi^-\pi^+$ (b), $\overline{\Xi}^+\pi^-$ (note that the $\overline{\Xi}(1530)°$ state is also visible) (c), and $\overline{\Xi}^+\pi^+$ (d). The shaded histograms are the normalized mixed-event backgrounds.

retained. The final data sample used for further analysis consisted of 1640 events containing one Ξ^- and 551 events containing one $\overline{\Xi}^+$.

To search for the exotic $\Xi^{--}_{3/2}$ the selected Ξ^- candidates were combined with primary π^- tracks. To select π^- from the primary vertex, their $|b_x|$ and $|b_y|$ had to be less than 1.5 and 0.5 cm, respectively, and their dE/dx had to be within 1.5σ of their nominal Bethe-Bloch value. Moreover, it was found from simulations that the signal to background ratio in the region of the already visible peak at about 1.86 GeV$/c^2$ is increased by the restriction $\theta > 4.5°$ (with θ the opening angle between the Ξ^- and the π^- in the laboratory frame). The resulting $\Xi^-\pi^-$ invariant mass spectrum is shown in Fig. 2(a). The shaded histogram is the mixed-event background, obtained by combining the Ξ^- and π^- from different events and normalizing to the number of real combinations. A significant narrow peak above the background is visible at approximately 1.86 GeV$/c^2$. This state is a candidate for the $\Xi^{--}_{3/2}$ pentaquark. The mass window 1.8500–1.8725 GeV$/c^2$ contains 81 entries with a background of about $B = 43$ events. For the signal of $S = 38$ events one obtains a significance of 4.2 standard deviations calculated from the simple formula $S/\sqrt{S + B}$. In addition, a Monte Carlo method [19] was used to estimate the probability that the observed peak is due to a fluctuation of the background. The contents of the bins of the background distribution were randomly fluctuated according to Poisson statistics. From many such trials the probability of observing a peak with 38 or more counts above the background in three adjacent bins was determined to be 3.1×10^{-5} for the mass interval 1.7–2.1 GeV$/c^2$ (covering the range of theoretical predictions) and 6.7×10^{-8} for the peak mass window. These probabilities correspond to 4.2σ and 5.4σ fluctuations of a Gaussian distributed background, respectively.

Of the other three members of the predicted isospin quartet only the $\Xi^0_{3/2}$ is observable in this experiment via the $\Xi^-\pi^+$ decay channel. The corresponding antibaryon states, $\overline{\Xi}^{++}_{3/2}$ and $\overline{\Xi}^0_{3/2}$, are also expected to be produced and should be detectable via the $\overline{\Xi}^+\pi^+$ and $\overline{\Xi}^+\pi^-$ decay channels, respectively. To reduce the proton and kaon contamination of the pion candidates in these decays, additional selection cuts were applied. A lower cut of 3 GeV$/c^2$ was imposed on the π^+ momenta to exclude the crossover region of the Bethe-Bloch curves where protons and pions cannot be distinguished. An asymmetric dE/dx cut between -0.5σ and 1.5σ around the nominal Bethe-Bloch values of the π^+ (in the $\Xi^-\pi^+$ spectra) and the π^- (in the $\overline{\Xi}^+\pi^-$ spectra) reduced the kaon contamination.

The mass distributions for $\Xi^-\pi^+$, $\overline{\Xi}^+\pi^-$, and $\overline{\Xi}^+\pi^+$ are plotted in Fig. 2(b)–2(d). Indeed, enhancements are seen in all three spectra. Fits to the combined signal of the $\Xi^{--}_{3/2}$ and its antiparticle and $\Xi^0_{3/2}$ and its antiparticle yield peak positions of 1.862 ± 0.002 GeV$/c^2$ and

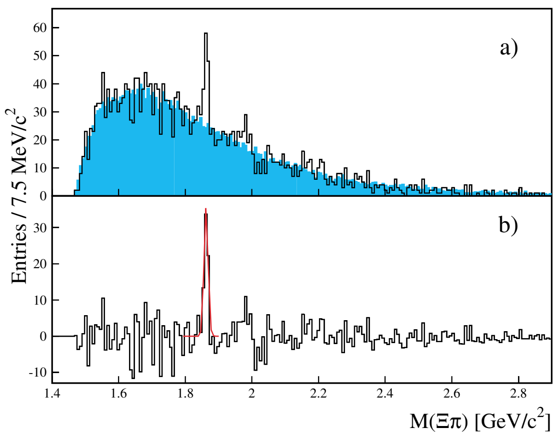

FIG. 3 (color online). (a) The sum of the $\Xi^-\pi^-$, $\Xi^-\pi^+$, $\overline{\Xi}^+\pi^-$, and $\overline{\Xi}^+\pi^+$ invariant mass spectra. The shaded histogram shows the normalized mixed-event background. (b) Background subtracted spectrum with the Gaussian fit to the peak.

1.864 ± 0.005 GeV$/c^2$. Compared to the $\Xi^{--}_{3/2}$, a smaller rate is expected for the $\Xi^0_{3/2}$ due to the additional cuts and the competing $\Xi^0\pi^0$ decay channel. Extrapolating from the yield ratio of about 0.5 between $\overline{\Xi}^+$ and Ξ^- [20], one also expects a weaker signal for the $\overline{\Xi}^{++}_{3/2}$ and $\overline{\Xi}^0_{3/2}$.

Since the two summed particle plus antiparticle mass spectra have their peaks at positions which are closer than the mass resolution of the detector, they can be added to determine a combined significance. The sum of the four mass distributions is displayed in Fig. 3(a). The signal is now $S = 69$ events over a background of $B = 75$, increasing the significance from the simple estimate $S/\sqrt{S+B}$ to 5.8σ. Figure 3(b) shows the combinatorial background subtracted distribution. A Gaussian fit to the peak yields a mass value of 1.862 ± 0.002 GeV$/c^2$ and a FWHM $= 0.017$ GeV$/c^2$ with an error of 0.003 GeV$/c^2$, largely due to the uncertainty in the background subtraction. The systematic error on the absolute mass scale determined from a fit to the $\Xi(1530)°$ (not shown) is below 0.001 GeV$/c^2$.

The detector response to the $\Xi^{--}_{3/2}$ resonance with a mass of 1.86 GeV$/c^2$ was estimated from simulation. The $\Xi^{--}_{3/2}$ was generated with zero mass width, a flat rapidity, and a thermal transverse momentum distribution with an inverse slope parameter of 160 MeV. These events were tracked through the detector using GEANT 3.21 followed by a full simulation of the NA49 apparatus response. They were then reconstructed with the same software as used for real events. The resulting mass distribution had a FWHM ≈ 0.018 GeV$/c^2$, consistent with the observed width of the $\Xi^{--}_{3/2}$ resonance peak. The same detector simulation chain was also applied to Λ and Ξ production. The curves in Fig. 1 demonstrate good agreement with the measured line shapes and thus confirm the reliability of the simulation.

The robustness of the $\Xi^{--}_{3/2}$ peak was investigated by varying the dE/dx cut used for particle selection, by changing the width of accepted regions around the nominal Ξ^- and Λ masses, by investigating different event topologies (e.g., the number of π mesons per event), by selecting tracks with different number of clusters, as well as by using different b_x and b_y cuts. Further, the influence of resonances (including the possibility of particle misidentification) which could affect the observed peak was checked by excluding them from the data. In all cases the peak at 1.86 GeV$/c^2$ proved to be robust. Events generated by the VENUS model [21] were used to verify that the peak is not an artifact of the reconstruction. Finally, a detailed visual inspection of computer displays of the events with $\Xi^{--}_{3/2}$ candidates did not reveal any obvious problem in their quality.

In summary, this analysis provides the first evidence for the existence of a narrow baryon resonance in the $\Xi^-\pi^-$ invariant mass spectrum with a mass of 1.862 ± 0.002 GeV$/c^2$ and a width below the detector resolution of about 0.018 GeV$/c^2$. The significance is estimated to be above 4.2σ. This state is a candidate for the exotic $\Xi^{--}_{3/2}$ baryon with $S = -2$, $I = \frac{3}{2}$, and a quark content of $(dsds\bar{u})$. Further, in the $\Xi^-\pi^+$ invariant mass spectrum at the same mass an indication is observed of the $\Xi^0_{3/2}$ member of this isospin quartet with a quark content of $(dsus\bar{d})$. Also, the corresponding antiparticle spectra show enhancements at the same invariant mass. Summing the four mass distributions increases the significance of the peak to 5.8σ.

The evidence for an exotic $\Xi^-\pi^-$ resonance together with the indication of a $\Xi^-\pi^+$ resonance at the same mass represents an important step towards experimental confirmation of the predicted baryon antidecouplet of pentaquark states. Definitive identification and exclusion of alternative interpretations require the determination of spin, parity, and isospin of the observed states.

This work was supported by the U.S. Department of Energy Grant No. DE-FG03-97ER41020/A000, the Bundesministerium für Bildung und Forschung, Germany, the Polish State Committee for Scientific Research (2 P03B 130 23, SPB/CERN/P-03/Dz 446/2002–2004, 2 P03B 02418, 2 P03B 04123), the Hungarian Scientific Research Foundation (T032648, T032293, and T043514), the Hungarian National Science Foundation, OTKA (F034707), and the Polish-German Foundation.

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