Pentaquark Search @ NA49. SPS. CERN

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As the first step of the pentaquark search at SPS, invariant mass spectra of baryonic resonances $\Xi^-\pi^-$, $\Xi^-\pi^+$, $\bar{\Xi}^+\pi^-$ and $\bar{\Xi}^+\pi^+$ are studied with the data in proton-proton collisions at $E_{Lab} = 158$ GeV/u obtained by the large acceptance NA49 detector at the CERN, SPS. A narrow resonance signal of $\Xi^-\pi^-$ is found at the mass of 1.862 ± 0.002 GeV/c^2 with its width of 0.018 GeV/c^2. This state is a strong candidate for the hypothetical exotic pentaquark baryon Ξ^{--} with S=-2, I=$\frac{3}{2}$ and a quark content of ($dds s\bar{u}$). At the same mass of the $\Xi^-\pi^+$ invariant mass spectrum a peak is observed as a candidate for the $\Xi^0_{3/2}$ with a quark content of ($dsus\bar{d}$). The corresponding antibaryon spectra also show enhancements at the same invariant mass.

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I. INTRODUCTION

Since an exotic baryon state Θ^+ with strangeness S=+1 and quark contents ($uudd\bar{s}$) in the decay channels nK^+ and pK^0_s with the mass predicted in [1] is firstly discovered by the LEPS collaboration in SPring-8 [2] and confirmed in several experiments over the world [3–8], theoretical as well as experimental pentaquark researches are prosperous in the hadron and nuclear physics. Pentaquark states have been theoretically investigated for a long while in the context of the constituent quark model [9–12]. Some of these states are expected to have *exotic* quantum numbers which cannot be explained by three-quark states. Using the chiral soliton model, an antidecouplet of baryons was predicted in [13, 14] and the lightest exotic baryon resonance with $S = +1, J^P = \frac{1}{2}^+$ is expected to exist at the mass of 1.530 GeV/c^2 with width of less than 15 MeV/c^2 in [1, 15], which was discovered and named as Θ^+ in above experiments. It was further predicted [1, 15, 17] that the antidecouplet also contains an isospin $\frac{3}{2}$ quartet of S=-2 baryons, consisting of two ordinary Ξ^0 and Ξ^-, and two additional exotic states of Ξ^+ and Ξ^{--} with quark contents ($uuss\bar{d}$) and ($ddss\bar{u}$), respectively. From the viewpoint of the mass for these heavier members of the antidecouplet, however, there are still contradictory predictions of 2.070 GeV/c^2 [1], 1.790 GeV/c^2 [16] and 1.750 GeV/c^2 [17], depending on their theoretical approaches to the isospin $\frac{3}{2}$ multiplet. The experimental research on the isospin multiplet of Ξs is therefore well motivated and represents an important step towards experimental confirmation of the predicted baryon antidecouplet of pentaquark states. Searching for the baryon resonances of Ξ^{--} and Ξ^0 (and their antibaryon resonances $\bar{\Xi}^{++}$ and $\bar{\Xi}^0$) the invariant mass spectra of $\Xi^-\pi^-$ and $\Xi^-\pi^+$ ($\bar{\Xi}^+\pi^-$ and $\bar{\Xi}^+\pi^+$) are presented [18–20].

II. THE NA49 EXPERIMENT

The NA49 spectrometer (described in detail in [21]) consists of two superconducting magnets (total bending power of 7.5 Tm) with TPCs - VTPC1 and VTPC2- (time projection chambers) inside the magnetic field, two additional TPCs - MTPC L/R - downstream of the magnets, and several TOF (time-of-flight) walls on both sides of the beam (Fig. 1). The TPCs (VTPC1/2 and MTPC-R/L) enable one to determine the spatial components of the momentum by measuring the curvature of a charged particle's trajectory in a given magnetic field. Extrapolating of the determined momentum vectors the position of the interaction point can be obtained. The momentum resolution of the spectrometer dp/p^2 is about 7×10^{-4} (GeV/c)$^{-1}$ for the tracks measured only in VTPC1, can be advanced upto 0.3×10^{-4} (GeV/c)$^{-1}$ taking into account tracks measured all TPCs. The specific energy loss dE/dx of charged particles measured in TPCs enables one to identify the particles with the well known Bethe-Bloch function (Fig. 2). The TOF informations are also available to enhance the particle identification (PID) efficiency for the particles, which cannot be well separated through the dE/dx-PID , e.g. kaon PID. About 6.5×10^6 events in proton-proton collisions at E_{Lab}=158 GeV/u ($\sqrt{s}$ = 17.2 GeV) were taken by the NA49 fixed target large acceptance hadron detector. A cylindrical hydrogen target with the geometry ϕ 2cm × Length 20cm is used for the interactions with the beam protons. 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.

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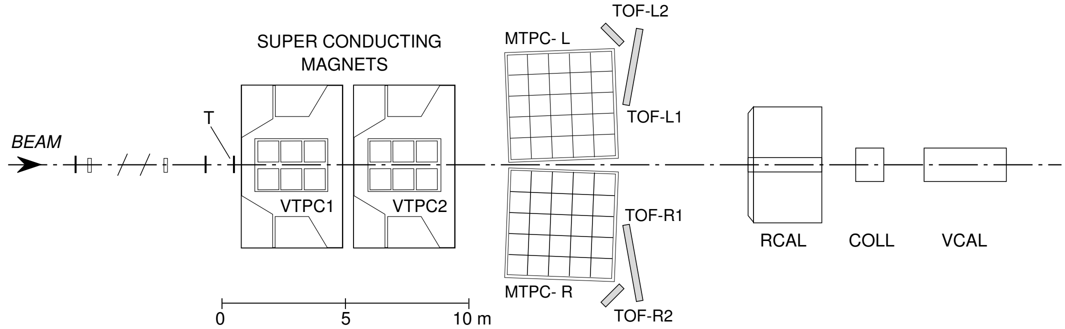

FIG. 1: A schematic overview of NA49 experimental apparatus showing the target T, the VTPCs within the superconducting magnets, the MTPCs and the TOF walls. The ground surface is about 6x13 m^2 without the calorimeters.

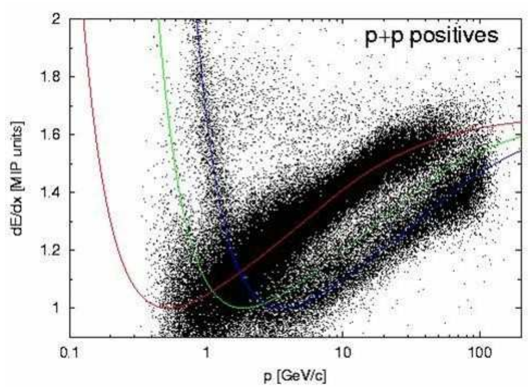

FIG. 2: Particle identification by the specific energy loss dE/dx.

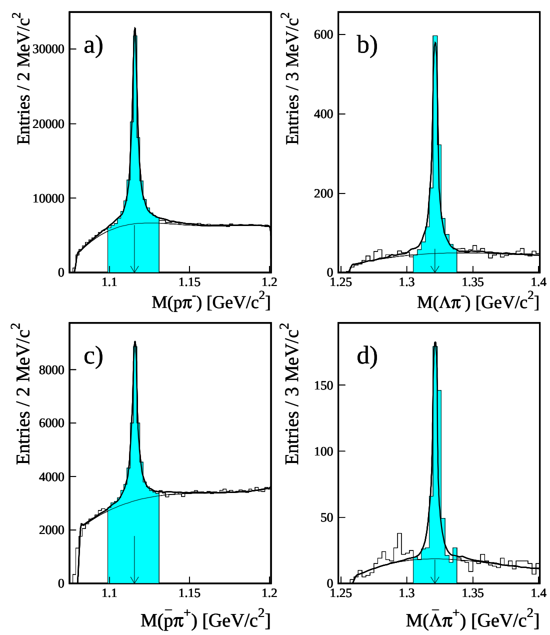

FIG. 3: (a) The $p\pi^-$ invariant mass spectrum for V0 topologies. (b) The $\Lambda\pi^-$ invariant mass spectrum for Ξ^- candidates. (c),(d) Analogous spectra for $\bar{\Lambda}$ and $\bar{\Xi}^+$.

III. DATA ANALYSIS

The data 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. Preferentially, to remove nontarget interact"ions the events were selected by the determined primary vertex position, which had to be within -9cm $\leq$ z $\leq$ 9cm and -1cm $\leq$ x,y $\leq$ 1cm from the center of target. This event selection reduced the data sample to 3.7×10^6 events. Particle identification was performed by using the specific energy loss dE/dx informations measured in TPCs. After careful calibration the dE/dx resolution 3-6% depending on the reconstructed track length is obtained. The dependence of dE/dx on velocity was fitted to a Bethe-Bloch type parametrization and this parameterized Bethe-Bloch function depending on momenta (solid lines in Fig. 2) is used for the nominal (theoretical) Bethe-Bloch values, around which the specific particle selection is accomplished.

For the first step to invariant mass spectra of $\Xi\pi$ the Λ candidates were found by pairing the identified protons and pions, of those the vertices from neutral decays (so-called V0s, mostly upstream of VTPC1) lie on the track with more VTPC points. A four-parameter fit was then performed to find V0 position along the longer track and the three momentum components of the other track at this point [22]. The resulting $p\pi^-$ ($\bar{p}\pi^+$) invariant mass spectrum is shown in Fig. 3(a) (Fig. 3(c)). Subsequently to find Ξ^- ($\bar{\Xi}^+$), the Λ ($\bar{\Lambda}$) cadidates within $\pm$ 15 MeV/c^2 (shaded area in Fig. 3(a) and (c)) around its nominal mass position (indicated as arrows in Fig. 3(a) and (c)) were combined with all π^- (π^+) performing the same fit procedure as for the V0 finding. Lastly invariant mass spectra $\Xi^-\pi^-$ and $\Xi^-\pi^+$ ($\bar{\Xi}^+\pi^+$ and $\bar{\Xi}^+\pi^-$) can

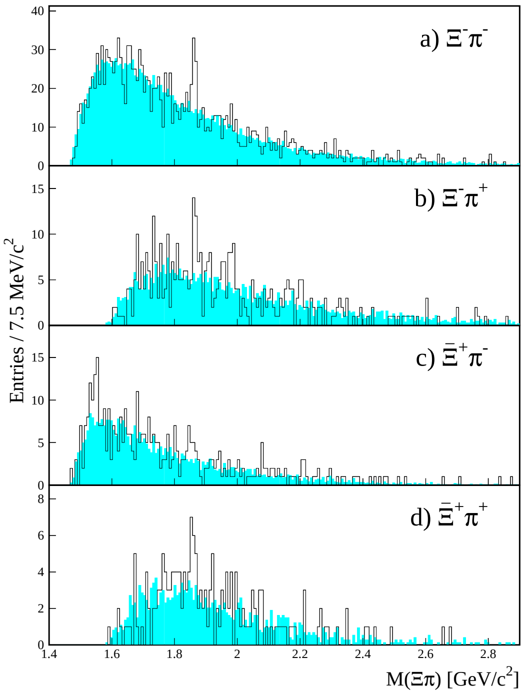

FIG. 4: Invariant mass spectra a"fter selection cuts for (a)$\Xi^-\pi^-$, (b)$\Xi^-\pi^+$, (c)$\bar{\Xi}^+\pi^-$ and (d)$\bar{\Xi}^+\pi^+$. The shaded histograms are the normalized mixed-event backgrounds.

be obtained in Fig. 4, combining Ξ^- ($\bar{\Xi}^+$) candidates to be within ± 0.015 GeV/c^2 around their nominal masses with primary pion tracks. To select primary pion tracks, their tracks were extrapolated to impact positions b_x and b_y, which had to satisfy the conditions $|b_x| \leq 1.5$cm and $|b_y| \leq 0.5$cm, and their dE/dx-values had to be within $^{1.5\sigma}_{-0.5\sigma}$ around their nominal Bethe-Bloch values. In order to reduce background and proton contamination in pion sample, some additional cuts ($p_{\pi^+} > 3$ GeV/c and θ_{lab} (between Ξ and π) $> 4.5^o$) are optionally imposed. More detailed descriptions of the analysis can be found in [18]. In Fig. 4 the mixed-event background histograms are shaded and overlapped, which are obtained via combinations of Ξ^- ($\bar{\Xi}^+$) and pions from different events and normalized to the number of real combinations.

IV. RESULTS

A significant narrow peak above the background at $\simeq$ 1.86 GeV/c^2 are observed in Fig. 4(a), which can be interpreted as a candidate of Ξ^{--} pentaquark baryon state. The significance of the peak is extracted from the signal and background in the mass window of 1.8500 - 1.8725 GeV/c^2 as $S/\sqrt{S+B} = 4.2$, which means 4.2 standard deviation of the background fluctuation. In the invariant mass spectrum of $\Xi^-\pi^+$ (Fig. 4(b)) an another member of the isospin $\frac{3}{2}$ quartet candidate Ξ^0 is visible at the same mass position and the resonance $\Xi(1530)^0$ is also clearly visible at the mass position of 1.532 ± 0.001 GeV/c^2, which indicates very small systematic error comparing with the PDG-value 1.5318 ± 0.00032 GeV/c^2. The corresponding antibaryon states, $\bar{\Xi}^{++}$ and $\bar{\Xi}^0$, are also expected and observed as shown in Fig. 4(c) and (d). Summing the particle and corresponding antiparticle histograms, one obtains the mass positions as $M_{\Xi^{--}(\bar{\Xi}^{++})} = 1.862 \pm 0.002$ GeV/c^2 and $M_{\Xi^0(\bar{\Xi}^0)} = 1.864 \pm 0.005$ GeV/c^2 with width about 18 MeV/c^2 in both cases. 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 delivered the mass position 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, mainly due to the uncertainty in the background substraction. In result the combined significance is obtained as 5.8σ.
Preliminarily the $\Xi(1530)^0\pi^-$ and $\Xi(1530)^0\pi^+$ resonances are searched to probe suggestions given in [23], and only in the invariant mass spectrum of $\Xi(1530)^0\pi^-$ a peak at 1.855 ± 0.003 GeV/c^2 is observed.

V. SUMMARY

A strong evidence for existence of a narrow $\Xi^-\pi^-$ resonance at 1.862 ± 0.002 GeV/c^2 ($\Gamma \leq 18$ MeV/c^2) is observed. The significance is estimated to be above 4.2σ. This state is a candidate for the exotic Ξ^{--} baryon with S=-2, I=$\frac{3}{2}$, and a quark content of ($ddss\bar{u}$). Further , at the same mass position a peak is observed in the $\Xi^-\pi^+$ spectrum, which is a candidate of a member of the isospin $\frac{3}{2}$ quartet Ξ^0 with a quark content of ($dsus\bar{d}$). The corresponding antibaryon spectra also show enhancements at the same mass. There is a preliminary evidence for existence of a narrow $\Xi(1530)^0\pi^-$ resonance at 1.855 ± 0.003 GeV/c^2. There is no indication for a $\Xi(1530)^0\pi^+$ resonance.

Acknowledgements

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[1] D. Diakonov, V. Petrov and M.V. Polyakov, Z.Phys. **A359** (1997) 305
[2] T. Nakano et al. (LEPS Collaboration), Phys. Rev. Lett. **91** (2003) 012002
[3] S. Stepanyan et al. (CLAS Collaboration), Phys. Rev. Lett. **91** (2003) 252001
[4] V. Barmin et al. (DIANA Collaboration), Phys. Atom. Nucl. **66** (2003) 1715
[5] J. Barth et al. (SAPHIR Collaboration), Phys. Lett. **B572** (2003) 127
[6] A. Airapetian et al. (HERMES Collaboration), hep-ex/0312044
[7] V. Kubarovsky et al. (CLAS Collaboration), Phys. Rev. Lett. **92** (2004) 032001
[8] A. Aleev et al. (SVD Collaboration), hep-ex/0401024
[9] R.L. Jaffe, in *Proceedings of the Topical Conference on Baryon Resonances, Oxford, U.K., 1976* (Rutherford Laboratory, Didcot, 1976)
[10] H. Hogaasen and P. Scorba, Nucl. Phys. **B145** (1978) 119
[11] D. Strottman, Phys. Rev. **D20** (1979) 748
[12] C. Roiesnel, Phys. Rev. **D20** (1979) 1646
[13] A. Manohar, Nucl. Phys. **B248** (1984) 19
[14] M. Chemtob, Nucl. Phys. **B256** (1985) 600
[15] M. Praszalowicz, in *Skyrmions and Anomalies*, edited by M. Jezabek and M. Praszalowicz (World Scientific, Singapore, 1987), p.112
[16] H. Walliser and V.B.Kopeliovich, J. Exp.Theor.Phys. **97** (2003) 433
[17] R.L. Jaffe and F. Wilczek, Phys. Rev. Lett. **91** (2003) 232003
[18] C. Alt et al. (NA49 Collaboration), Phys. Rev. Lett. **92** (2004) 042003
[19] K. Kadija, Quark Matter 2004 Presentation, http://www-rnc.lbl.gov/qm2004/talks/parallel/Friday03/KKadija_PPTWin.PPT
[20] I.-K. Yoo, Multiquark Workshop Presentation, http://www2.yukawa.kyoto-u.ac.jp/~mquark04/files/18/mq04_Yoo.pdf
[21] S. Afanasiev et al. (NA49 Collaboration), Nucl. Instr. Meth. **A430** 210
[22] D. Barna, Ph.D. thesis, KFKI Research Institute for Nuclear Physics, Budapest, 2002 http://na49info.cern.ch/cgi-bin/wwwd-util/NA49/NOTE?291
[23] R.L. Jaffe and F. Wilczek, Phys.Rev. D69 (2004) 114017