Pentaquark Searches at CDF*

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Recently there has been revival of interest in exotic baryon spectroscopy triggered by experimental evidence for pentaquarks containing u, d, s and c-quarks. We report results of the searches for pentaquark states in decays to pK_S^0, $\Xi^- \pi^\pm$ and $D^{*-}p$ performed at CDF detector using 220 pb^{-1} sample of $p\bar{p}$ interactions at $\sqrt{s}$ of 1.96 TeV. No evidence for narrow resonances were found in either mode.

1. Introduction

Searches for states, characterized by so-called exotic quantum numbers, i.e., quantum numbers that cannot be obtained from minimal $(q\bar{q})$ or (qqq) configurations of standard mesons and baryons, have taken place since the introduction of QCD and quark model. Until recently, these searches yielded very little conclusive evidence for such states.

During 2003, however, the situation has changed dramatically. An observation of a narrow resonance at (1540 ± 10) MeV/c^2, called Θ^+, decaying to nK^+, produced in $\gamma n \to K^- \Theta^+$, was reported by LEPS [1]. The state has exotic quantum number, positive strangeness, and cannot exist in a simple three-quark model. A pentaquark interpretation was employed suggesting the quark content to be $(uudd\bar{s})$. This observation was confirmed by various experiments using incident beams of real and quasi-real photons, kaons and neutrinos [2].

Afterwords, followed two other manifestly exotic S=-2 baryon states decaying to $\Xi^- \pi^\pm$ in pp collisions of CERN SPS at $\sqrt{s} = 17.2$ GeV, reported by NA49 [3]. The combined mass of $\Xi_{3/2}^{--}$ and $\Xi_{3/2}^0$ was measured to be (1.862 ± 0.002) GeV/c^2. These resonances were interpreted as $I_3 = -3/2$ and $I_3 = +1/2$ partners of isospin quadruplet of five-quark states with quark contents $(dsds\bar{u})$ and $(dsus\bar{d})$ respectively.

The Θ^+ and $\Xi^{--,0}$ states are consistent with being members of minimal $SU(3)$ anti-decuplet of pentaquark states predicted in the chiral soliton model of baryons [4].

In March 2004, the H1 experiment at HERA reported a narrow resonance, the Θ_c, decaying to $D^{*-}p$ at a mass 3.099 GeV/c^2 [5]. It can be seen as the charmed analog of Θ^+ with quark content $(uudd\bar{c})$.

For strongly decaying particles all reported states are unusually narrow with widths consistent with detector resolution. The reported masses of Θ^+ vary widely over a range, between 1526 and 1542 MeV/c^2, for different experiments.

All pentaquark observations are based on relatively small data samples. Typically $20 - 100$ signal events are seen with a significance in the range from 4 to 6σ. While the Θ^+ has been seen by several experiments, an independent confirmation of the $\Xi_{3/2}^{--,0}$ and Θ_c states has not been made. Definitely high statistics experiments are needed to establish pentaquark states unambiguously.

At this conference we report results of the searches for exotic baryons Θ^+, $\Xi_{3/2}^{--,0}$ and Θ_c, produced in quark fragmentation in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, using data recorded with upgraded CDF II detector at Tevatron, Fermilab.

2. The data samples

The data used in this analysis were obtained through three different trigger paths. The first data set was obtained by a trigger that was specialized for recording hadronic B-decays, the so-
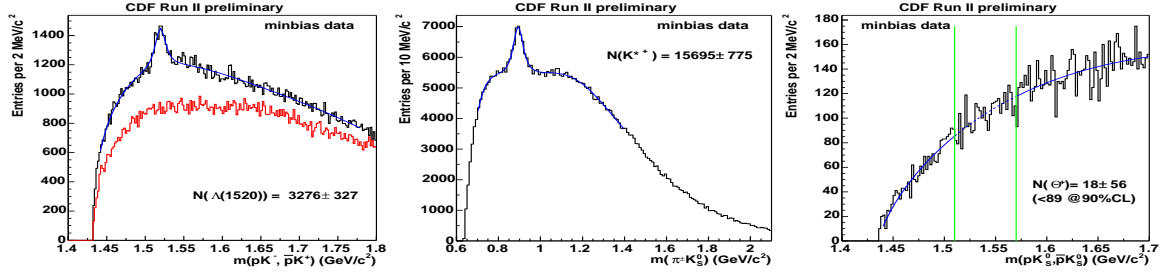
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*Presented at 6th International Conference on Hyperons, Charm and Beauty Hadrons, BEACH 2004, June 27 - July 3, 2004, IIT, Chicago, U.S.A.

Figure 1. Left: an invariant mass spectrum of the pK^- (and pK^+) combinations showing well established resonance $\Lambda(1520)$. Center: a $K_S^0\pi^+$ invariant mass spectrum showing clear K^{*+} signal. Right: an invariant mass spectrum of pK_S^0 combinations, two vertical lines indicate the Θ^+ search window

called B-hadronic trigger. It requires the presence of two displaced oppositely charged tracks with hits in silicon, each having $p_T > 2$ GeV/c, the scalar sum of the two transverse momenta exceeding 5.5 GeV/c^2 and an impact parameter greater than 0.1 mm. The other two complimentary datasets were produced by the Jet20 trigger, which requires the presence of a jet with an $E_T > 20$ GeV and a minimum bias trigger, which selects soft inelastic collisions. The data corresponded to an integrated luminosity of 220-240 pb^{-1}. The Jet20 and the minimum bias triggers are heavily prescaled resulting in effective integrated luminosities 0.36 pb^{-1} and 0.37 nb^{-1} correspondingly.

3. Search for $\Theta^+ \to pK_S^0$

In contrast to nK^+ channel, the decay $\Theta^+ \to pK^0$ does not provide manifestly exotic signature as the K^0 is reconstructed as K_S^0. However observation or non-observation of a narrow state decaying to pK_S^0 at the same mass as in nK^+ channel can be interpreted as positive confirmation or evidence against the existence of Θ^+ as this state is expected to decay to $\Theta^+ \to pK^0$ and nK^+ with the same rate.

Table 1
Event yields of reconstructed resonances and 90% CL limits on Θ^+ yields

Resonance	Minbias data	Jet20 data
$\Lambda(1520)$	3276 ± 327	4915 ± 702
K^{*+}	15695 ± 775	35769 ± 1390
Θ^+	18 ± 56	-56 ± 100
90% CL on Θ^+	< 89	< 76

The information from TOF system has been used to produce clean samples of protons. Protons were identified as tracks having 2σ separation between TOF assuming proton and kaon hypotheses. Figure 1 shows from left to right invariant mass spectra of pK^-, $K_S^0\pi^+$ and pK_S^0 combinations in the minimum bias dataset. Clear signals from known resonances $\Lambda(1520)$ and K^{*+} can be seen. There is no indication of a narrow state in pK_S^0 mass spectrum. The spectrum was fit to the background function with the search mass window $1.510 < M(pK_S^0) < 1.570$ GeV/c^2 excluded from the fit. Table 1 summarizes the yields of known resonances and 90% CL limits on Θ^+ yields in the minimum bias data and in the Jet20 data.

4. Search for $\Xi_{3/2}^{--,0}$

The pentaquark candidates were reconstructed through the decay chain: $\Xi_{3/2}^{--,0} \to \Xi^- \pi^{-,+}$, $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$. The Λ candidates were reconstructed from oppositely charged pairs of tracks. The track with the highest transverse momentum in the pair was assigned the proton mass.

The long lifetime of the Ξ^- and the p_T requirements produce a decay point of the Ξ^- that lies outside the SVX II volume in a significant fraction of events. This makes it possible to reconstruct the Ξ^- track from the hits that the particle has left traversing the layers of SVX II. The position of the Ξ^- decay and its momentum information obtained in the mass constrained fit were used to define a road for a special reconstruction al-
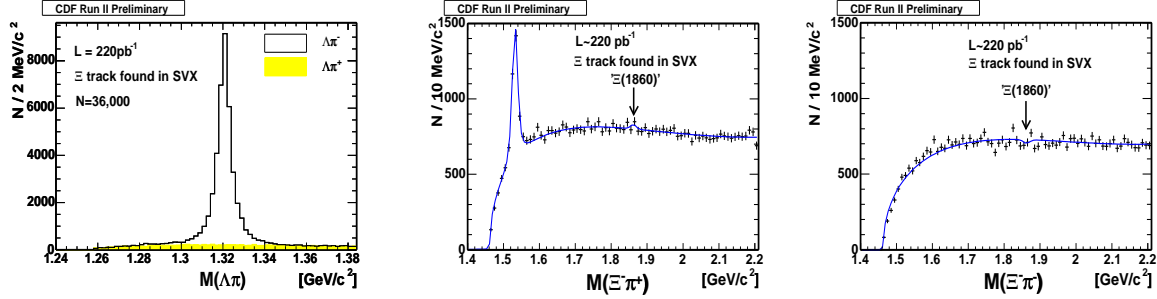
Figure 2. Left: an invariant mass spectrum of $\Lambda\pi$ combinations that have associated Ξ track in SVX, open histogram shows right sign $\Lambda\pi^-$ combinations, filled histogram shows wrong sign, $\Lambda\pi^+$ combinations. Center: an invariant mass of $\Xi^-\pi^+$ combinations. Right: an invariant mass of $\Xi^-\pi^-$ combinations. Arrows mark the mass at 1862 GeV/c^2.

Table 2
Event yields of $\Xi(1530)$ and upper limits at 90%CL on event yields and relative rates $\Xi^{--}_{3/2}$ and $\Xi^0_{3/2}$ assuming equal detector acceptance of $\Xi^{--,0}_{3/2}$ and $\Xi^(1530)$.

	Hadronic trigger	Jet20 data
N(Ξ)	35722 ± 326	4870 ± 122
N($\Xi(1530)$)	2182 ± 92	387 ± 34
N($\Xi^{--}_{3/2}$)	-54 ± 47 (< 51 @ 90% CL)	-4 ± 18 (28 @ 90% CL)
N($\Xi^0_{3/2}$)	57 ± 51 (< 126 @ 90% CL)	-14 ± 19 (25 @ 90% CL)
$\frac{\sigma(\Xi^{--}_{3/2})\cdot Br(\Xi\pi^-)}{\sigma(\Xi(1530))\cdot Br(\Xi\pi^+)}$	< 0.03 @ 90% CL	< 0.07 @ 90% CL
$\frac{\sigma(\Xi^0_{3/2})\cdot Br(\Xi\pi^+)}{\sigma(\Xi(1530))\cdot Br(\Xi\pi^+)}$	< 0.06 @ 90% CL	< 0.06 @ 90% CL

gorithm that tracks the Ξ^- in the silicon system. This algorithm required a minimum of two axial SVX hits on the track within the radius defined by the measured decay point. A plot on the left of the Figure 2 shows the $\Lambda\pi^-$ invariant mass of Ξ^- candidates that have associated SVX tracks. A very clean Ξ^- signal containing 36,000 events is visible. The Ξ^- sample used in subsequent analysis was limited to candidates that were successfully tracked in the silicon detector, and had invariant mass within 10 MeV/c^2 of the world average Ξ^- mass.

To search for new states, the Ξ^- tracks in each event were combined with the remaining tracks. These tracks were assigned the pion mass, and were refit with the constraints that they form a good vertex with Ξ track and the total momentum of the pair was constrained to point back to the primary vertex.

The invariant mass spectra of $\Xi^-\pi^+$ and $\Xi^-\pi^-$

are shown in Figure 2. A prominent peak corresponding to the decay $\Xi(1530) \to \Xi^-\pi^+$ can be clearly seen. No other peaks are visible in either $\Xi^-\pi^+$ nor $\Xi^-\pi^-$ spectra. The expected detector resolution at 1862 GeV/c^2 is 8 MeV/c^2. Table 2 summarizes the measurements for hadronic sample and Jet20 sample.

5. Search for $\Theta^0_c \to D^{*-}p$

This mode is especially attractive as two tracks from displaced D^0 vertex come in on unique CDF B-hadronic trigger. In the H1 pentaquark paper they mentioned that the fraction of Θ^0_c is roughly 1% of the total D^* production [5]. Assuming that the dominant production mechanism of Θ^0_c in deep inelastic ep collisions is fragmentation of the c-quark produced in $\gamma^*p \to c\bar{c}$, the fragmentation probability $f(\bar{c} \to \Theta^0_c)$ could be 2.35×10^{-3}. If this was true then CDF should see $\sim 10^4$ per 100 pb^{-1} [6].
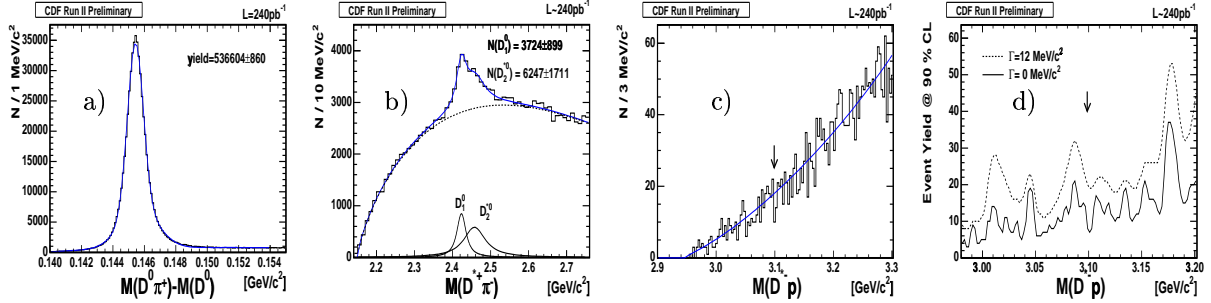
Figure 3. a) $D^0\pi^+$ mass difference spectrum, b) $\Delta M(D^{*+}\pi^-) + 2.01$ spectrum, c) $\Delta M(D^{*-}p) + 2.01$ mass spectrum, d) upper limits on event yield vs mass obtained assuming zero natural width of Θ_c (solid line) and 12 MeV/c^2 (dashed line). Arrow marks the mass at 3.099 GeV/c.

Table 3
Event yields and upper limits at 90%CL on event yields of Θ_c

Channel	yield
$N(D_2^{*0}) \to D^{*+}\pi^-$	6247 ± 1711
$N(D_1^0) \to D^{*+}\pi^-$	3724 ± 899
$\Theta_c \to D^{*-}p$	< 21 @ 90 % CL

The CDF experiment has accumulated 540,000 D^{*+} candidates, very cleanly reconstructed in $D^0\pi^+$, $D^0 \to K^-\pi^+$ chain (see Figure 3(a)). An ability to reconstruct reference $D^{**} \to D^{*+}\pi^-$ channel is demonstrated in Figure 3(b).

The proton identification procedure was based on combined likelihood ratio calculated from measurements of specific ionization and time-of-flight for allowed mass hypotheses (e, μ, π, K and p). A track was treated as proton if the corresponding likelihood ratio exceeded 40%.

The $D^{*-}p$ mass difference spectrum $M(D^{*-}p) = \Delta M(D^{*-}p) + 2.01$ is presented in Figure 3(c), there is no apparent narrow resonance signal. The expected mass resolution at 3.099 GeV/c^2 is 2.3 MeV/c^2. The function superimposed in Figure 3(c) shows the result of the unbinned log-likelihood fit with the background function consisting of square root threshold function multiplied by the 3rd order polynomial. A series of such fits were performed with Θ_c^0 signal introduced as Breit-Wigner resonance function convoluted with a Gaussian resolution function. The mass of the state was varied from 2.98 to 3.2 GeV/c^2 with 2 MeV/c^2 step. The result-

ing functions of 90% CL event yield limits vs $D^{*-}p$ mass are shown in Figure 3(d) for two cases – assuming zero natural width and assuming 12 MeV/c^2 natural width of the resonance. As the final result we quote the worst upper limit obtained within the allowed search window (3.099 ± 0.018) MeV/c^2. All results are summarized in Table 3.

6. Conclusion

Using high statistics samples of K_S^0, Ξ^- and D^{*+} produced in p$\bar{\text{p}}$ interactions at $\sqrt{s}$=1.96 TeV and reconstructed with the detector having excellent momentum resolution and a powerful particle identification system we performed a sensitive search for narrow pentaquark states decaying to pK_S^0, $\Xi^-\pi^\pm$ and $D^{*-}p$. No signal found in either channel. The analysis technique was tested by demonstrating the ability to reconstruct signals from standard narrow resonances having similar decay kinematics, $\Lambda(1520)$, K^{*+}, $\Xi(1530)$, D^{**}. The absence of pentaquark signals means that, if existent, pentaquarks are not produced in the process of quark fragmentation or such production is severely suppressed.

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