Searches for Pentaquarks at CDF

Dmitry Litvintsev
MS318, Fermilab, PO Box 500, Batavia, Illinois, 60510-0500, USA
E-mail: litvinse@fnal.gov

Abstract.
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 $\Xi^-$, $D^*$, and $D^0$ 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 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. 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 $(1540 \pm 10)$ MeV/$c^2$, called $\Theta^+$, decaying to $nK^+$, produced in $\gamma n \rightarrow K^-\Theta^+$, 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].

Later, 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 [4]. The combined mass of $\Phi^{--}$ and $\Phi^0$ was measured to be $(1.862 \pm 0.002)$ 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 $\Theta^+$ and $\Phi^{--,0}$ states are consistent with being members of minimal SU(3) anti-decuplet of pentaquark states predicted in the chiral soliton model of baryons [3].

Recently the H1 Collaboration observed a narrow peak in $D^*\bar{p}$ invariant mass spectrum from what is believed to be an anti-charmed pentaquark baryon state with $(\bar{c}dudu)$ quark content, produced in deep inelastic scattering in $ep$ collisions at HERA. This new state was tentatively named $\Theta^0_c$ as being an anti-charmed analog of $\Theta^+$ pentaquark.

However, all pentaquark observations are based on relatively small data samples. While the $\Theta^{--}$ has been seen by several experiments, an independent confirmation of the $\Phi^{--,0}$ and $\Theta_c$ states has not been made. Definitely high statistics experiments are needed to establish pentaquark states unambiguously.

In this paper we describe searches for double strange pentaquarks $\Phi^{--,0}$ and (anti)charmed pentaquark states using data produced in $p\bar{p}$ collision at $\sqrt{s} = 1.96$ TeV and recorded with the
upgraded CDFII detector at Tevatron, Fermilab.

2. The data samples
The data used in this analysis were obtained through two different trigger paths. The first data set was obtained by a trigger that was specialized for recording hadronic B-decays, so-called Silicon Vertex Trigger (SVT). The trigger requires presence of two oppositely charged tracks each having $p_T > 2$ GeV/c and impact parameter with respect to the beam ($d_0$) to fall within the range $120 \, \mu m < |d_0| < 1$ mm. In addition a scalar sum of two tracks’ transverse momenta is required to be greater than 5.5 GeV/c.

The other, complimentary dataset, was produced by the Jet20 trigger, which requires the presence of a jet with an $E_T > 20$ GeV.

The data corresponded to an integrated luminosity of 220-240 pb$^{-1}$. The Jet20 trigger is heavily prescaled resulting in effective integrated luminosity of 0.36 pb$^{-1}$.

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

![Figure 1](attachment:image.png)

**Figure 1.** Left: an invariant mass spectrum of $\Lambda\pi$ combinations that have associated $\Xi$ 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$^2$.

The long lifetime of the $\Xi^-$ and the $p_T$ requirements produce a decay point of the $\Xi^-$ that lies outside the SVX II volume in a significant fraction of events. This makes it possible to reconstruct the $\Xi^-$ track from the hits that the particle has left traversing the layers of SVX II. The position of the $\Xi^-$ decay and its momentum information obtained in the mass constrained fit were used to define a road for a special reconstruction algorithm that tracks the $\Xi^-$ 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 1 shows the $\Lambda\pi^-$ invariant mass of $\Xi^-$ candidates that have associated SVX tracks. A very clean $\Xi^-$ signal containing 36,000 events is visible. The $\Xi^-$ 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 $\Xi^-$ mass.

To search for new states, the $\Xi^-$ 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 $\Xi$ 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 1. A prominent peak corresponding to the decay $\Xi(1530) \rightarrow \Xi^−\pi^+$ 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 1 summarizes the measurements for hadronic sample and Jet20 sample.

4. Search for Charmed Pentaquarks at CDF

The SVT trigger efficiently selects very clean samples of $D$-mesons making CDF especially sensitive to pentaquarks decaying to $D$-mesons+proton in the final state. The H1 Collaboration found that the fraction of $\Theta^0$ is roughly 1% of the total $D^*$ production [5]. Assuming that the dominant production mechanism of $\Theta^0$ in deep inelastic $ep$ collisions is fragmentation of the $c$-quark produced in $\gamma^* p \rightarrow c\bar{c}$, the CDF should see $\sim 10^4$ per 100 pb$^{-1}$ [6].

We searched for pentaquarks strongly decaying to $D^{*-}p$, $D^−p$, $\bar{D}^0p$ and $D^0p$ with subsequent decays $D^{*-} \rightarrow D^0\pi^−$, $D^{−} \rightarrow K^+\pi^−\pi^−$ and $D^0 \rightarrow K^+\pi^−\pi^−$. No kinematic cuts were applied to pentaquark candidates except the requirement that two oppositely charged tracks contributing to pentaquark candidate passed SVT trigger track matching. Vertex fit quality cuts, mass windows and vertex constraints were worked out on reference $D^{**}$ signals having similar $D$-meson+track final states and similar decay kinematics. The proton identification procedure was based on combined likelihood ratio calculated from measurements of specific ionization and time-of-flight for allowed mass hypotheses ($e$, $\mu$, $\pi$, K and $p$). A track was treated as proton if the corresponding likelihood ratio exceeded 40%.

The reference $D^{**}$ signals are shown in the top row of histograms in Figure 2. High statistics signals from $D_2^{0*0} \rightarrow D^{*+}\pi^−$, $D_1^0 \rightarrow D^{*+}\pi^−$, $D_2^{*0} \rightarrow D^+\pi^−$ and $D_2^{*+} \rightarrow D^−\pi^+$ decays can be seen in corresponding invariant mass spectra. Feed-downs from $D^{**}$ decays involving lost neutrals are present as broad lower mass bumps in $D^+\pi^−$ and $D^0\pi^+$ spectra with the latter dominated by huge $D^{*+} \rightarrow D^0\pi^+$ signal at the threshold. The invariant mass spectra of $D^{*-}p$, $D^{-}p$ and $\bar{D}^0p$ are shown in the lower row of Figure 2. Arrows mark position of the $\Theta_c$ pentaquark. The expected detector mass resolution at 3.099 GeV/c$^2$ is 2.4 MeV/c$^2$ for $D^{*-}p$ mode and $\sim 3$ MeV/c$^2$ for $D^{-}p$ and $D^0p$ modes. Apparently no narrow peaks are seen. The superimposed curves show the results of unbinned maximum likelihood fits using background function consisted of polynomials multiplied by exponential threshold factors. Table 2 summarizes event yields in reference modes and upper limits on charmed pentaquark event yields at 90%.

5. Conclusion

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

**References**

[1] T. Nakano et al., Phys. Rev. Lett. 91, 012002
[2] V. V. Barmin et al., Phys. Atom. Nucl. 66, 1715; J. Barth et al. Phys. Lett. B 572 127; A. E. Asratyan et al., Phys. Atom. Nucl. 67, 682; V. Kubarovsky et al., Phys. Rev. Lett. 92, 032001; A. Airapetian et al., Phys. Lett. B 587 213
[3] A. Diakonov et al., Z. Phys. A 359 305
[4] C. Alt et al., Phys. Rev. Lett. 92, 042003
[5] A. Aktas et al. [H1 Collaboration], Phys. Lett. B 588, 17 (2004)
[6] K. Cheung, arXiv:hep-ph/0405281