Search for exotic baryons in 800 GeV/c $pp \rightarrow pX$

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Abstract.

We present preliminary results of the search for the pentaquark candidates $\Theta(1540)$ and $\Xi(1862)$ using data from Fermilab experiment E690 in the reaction $pp \rightarrow pX$ at 800 GeV/c. We find that production of pentaquark resonances is heavily suppressed with respect to the production of normal baryon and antibaryon resonances.

1. Introduction

Besides meson and baryon resonant states, made of two and three quarks, respectively, QCD allows the existence of resonant states of more than three quarks, states with two quarks and a valence gluon (hybrid states), or even resonant states including no valence quarks (glueballs.) States with five quarks (pentaquarks) have been searched for long ago [1]. One of the first candidates for a resonant pentaquark state was $\Lambda(1405)$. Since its spectrum could be dynamically generated, it was proposed that this state was a molecular meson-baryon bound state [2]. However, the assumed quark content of $uuds\bar{u}$ was ambiguous, due to similar properties of the three quark state $uds$. This type of ambiguity is not present in some states recently reported in the literature. Based on the work of Diakonov, Petrov and Polyakov [3], the LEPS Collaboration studied the production of resonant states close to $NK$ threshold, in the reaction [4]

$$\gamma n \rightarrow K^- K^+ n.$$ (1)

They found a narrow resonance with a mass of about 1540 MeV/c$^2$ and a width of 25 MeV. The quark content of this state was $uudds$, and strangeness of $S = +1$. This isosinglet state $\Theta^+$ was seen in the decay

$$\Theta^+ \rightarrow nK^+ ,$$ (2)

but the decay to $pK_0^+$ is also allowed. Subsequently, the DIANA Collaboration at ITEP [5], CLAS at Jefferson Lab [6], and SAPHIR at ELSA [7], claimed observation of this same state. All experiments reported roughly the same mass and width.
Based on the $\Theta^+$ result, and on a diquark model for exotic dynamics, R. Jaffe and F. Wilczek predicted a narrow “cascade” baryon with charge -2 and strangeness -2, at 1750 MeV/$c^2$ [8]. This state may have already been observed in proton-proton collisions at $\sqrt{s}=17.2$ GeV by the NA49 Collaboration [9], in the decay

$$\Xi(1862) \rightarrow \Xi(1320)\pi$$  \hspace{1cm} (3)

The $\Xi(1862)$ would have $I=3/2$, and the decays observed by NA49 are to

$$\Xi^-\pi^- , \, \Xi^-\pi^+ , \, \Xi^+\pi^- , \, \Xi^+\pi^+ ,$$  \hspace{1cm} (4)

The reported width of this state is about 18 MeV.

Although these states may have been seen in different experiments, there exist experimental questions to be answered before claiming solid evidence for pentaquark resonances. In the particular case of the $\Theta(1540)$, the low statistics used in the different analysis, the large signal to background ratio reported, and the large $\Theta(1540)/\Lambda(1520)$ ratio, make it difficult to accept a solid identification of a $S=+1$ baryon state. Moreover, there are indications that kinematic reflections of meson resonances could account for the $\Theta(1540)$ signal [10]. In the case of the $\Xi(1862)$, it has been argued that the NA49 results are inconsistent with the vast amount of existing data on $\Xi$ spectroscopy [11]. In any case, it is important to confront these results with experimental studies performed on clean event samples and high statistics, in order to settle this subject.

In this work we report preliminary results of the search for the pentaquark candidates $\Theta(1540)$ and $\Xi(1862)$ using more than 4.5 billion events collected by the E690 Collaboration during Fermilab 1991 fixed target run.

2. E690 spectrometer

The E690 apparatus consisted of a high rate, open geometry multiparticle spectrometer used to measure the target system ($X$) in reactions

$$pp \rightarrow p_{\text{fast}}X ,$$  \hspace{1cm} (5)
and a beam spectrometer used to measure the incident 800 GeV/c beam and scattered proton. A liquid hydrogen target was located just upstream of the multiparticle spectrometer. The 96 cell Cherenkov counter located at the downstream end of the main spectrometer magnet used Freon 114 as a radiator, and had a pion threshold of 2.57 GeV/c. The E690 apparatus has been described elsewhere [12]. The same apparatus had been used for experiment BNL 766, where very good mass resolution measurements were performed [13].

3. Data analysis

We selected events for two types of reaction. First, we selected events for the inclusive reaction

\[ pp \rightarrow p_{fast} \Xi^{\pm} \pi^{\pm} X, \quad \Xi \rightarrow \Lambda \pi \]  

(6)

and, second, for the exclusive reaction

\[ pp \rightarrow p_{slow} K_s K^- \pi^+ p_{fast} \]  

(7)

In either case, the primary vertex was constrained to lie on the incoming beam trajectory.

For events in reaction (6), with “Vee” topology, tracks were refitted with the geometrical constraint that the daughter vertex must point back to the parent vertex; no mass constrained fit was imposed. We found 512,850 events with \( \Xi^- \) assigned to the primary vertex, and 153,671 events with \( \Xi^+ \). In the upper plots of Fig.1 we show the \( \Lambda \pi \) invariant mass distributions for the selected events, and in the lower plots the corresponding \( p\pi \) invariant mass distributions for the \( \Xi \rightarrow \Lambda \pi \) decays. As can be seen, the data has very little background.

In Fig.2 we show the four \( \Xi^{\pm} \pi^{\pm} \) effective mass spectra for events in reaction (6). The average number of mass combinations per event are 3.5 times for \( \Xi^- \pi^+ \), 2.0 times for \( \Xi^+ \pi^- \), 2.6 times...
Figure 3. Events in reaction (7) without cuts (upper plots), and with $\Delta E - p_L$ (lower left) or $\Delta p_T^2$ cut (lower right).

for $\Xi^+\pi^-$, and 2.7 times for $\Xi^+\pi^+$. The $\Xi^-\pi^+$ and $\Xi^+\pi^-$ effective mass distributions show clear narrow $\Xi(1530)$ peaks of about 14 MeV/c width. On the contrary, the $\Xi^-\pi^-$ and $\Xi^+\pi^+$ effective mass distributions do not show any resonant structure. The arrows in these plots are at 1750 and 1860 MeV/c$^2$. The Monte Carlo mass resolution ($\sigma$) for $\Xi\pi$ is 3.3 MeV at 1750 MeV/c$^2$, and 4.5 MeV at 1862 MeV/c$^2$. For the $\Xi^-\pi^+$ events, we find about 70,000 $\Xi(1530)$, while for the $\Xi^-\pi^-$ events, we estimate that the yield of a narrow resonant structure at 1862 MeV/c$^2$ is less than 200 events (95% CL), while for the $\Xi^+\pi^+$ events, the yield is less than 120 events (95% CL.)

Events in the exclusive reaction (7) where selected to satisfy the required topology by imposing energy and momentum conservation. Due to the low multiplicity in this reaction, combinatorics are very limited. In the selection process we imposed a loose cut on the conservation of longitudinal momentum (5 GeV/c), but we applied tight cuts on the overall $p_T^2$ and $E - p_L$. For the $p_T^2$ conservation we required that $p_T^2 < 0.002$ GeV$^2$/c$^2$. We imposed $E - p_L$ conservation because errors in these two variables are highly correlated in central production. We required that $-0.2 < E - p_L < 0.15$ GeV. We also required that these cuts eliminated events consistent with topology of $p_{\text{slow}} K_s K^+ \pi^- p_{\text{fast}}$, which would not give the adequate strangeness for $\Theta^+$ decays.

The energy momentum conservation cuts are depicted in Fig.3. The two upper plots in show the overall $p_T^2$ and $E - p_L$ distributions for all events with the required topology. The two lower plots show the same distributions but with cut on the other variables. 68,050 events were selected with these cuts. Of these, only 6% had two solutions per event, corresponding to $\pi^+/p_{\text{slow}}$ ambiguity.

As it is shown in Fig.4, many well known resonances can be seen in these events. The $K\pi$ invariant mass distributions shown in this figure have very clear $K^*(890)$ peaks, the $K_s K^-\pi^+$
Figure 4. $K_s\pi^+$, $K_sK^-\pi^+$, $K^-\pi^+$ and $pK^-$ invariant mass distributions for events in reaction (7).

The invariant mass distribution has clear narrow $f_1(1285)$ and $f_1(1420)$ peaks, and the $pK^-$ invariant mass distribution has a clear narrow $\Lambda(1520)$ peak.

In Fig. 5 we compare the $pK^0_s$ and $pK^-$ invariant mass distributions. The $pK^-$ effective mass shows about 5000 $\Lambda(1520)$ events above background, with a FWHM of about 14 MeV. However, there is no indication of any resonance structure in the $pK^0_s$ effective mass distribution below 1.7 GeV/c$^2$. The Monte Carlo $pK^0_s$ mass resolution ($\sigma$) at 1540 MeV is 1.5 MeV. The estimated yield of a narrow $pK^0_s$ resonance at 1540 MeV is less than 25 events (95% CL.)

4. Conclusions

We reported here the search for exotic baryons in 800 GeV/c $pp \rightarrow pX$ using the FNAL-E690 spectrometer.

In an inclusive study of $\Xi^\pm\pi^\pm$ events, we observed strong signals for $\Xi(1530)$ and $\Xi(1530)$, but no other mass peaks were observed. The number of $\Xi^-\pi^-$ produced at 1862 MeV in a narrow resonance is less than 0.3% of the observed number of $\Xi(1530) \rightarrow \Xi^-\pi^+$ decays. The number of $\Xi^+\pi^+$ produced at 1862 MeV in a narrow resonance is less than 0.8% of the observed number of $\Xi(1530) \rightarrow \Xi^\mp\pi^-$ decays.

In a study of the exclusive reaction $pp \rightarrow p_{\text{slow}}K_sK^-\pi^+p_{\text{fast}}$, strong signals are observed for a number of well-established meson and baryon resonances. However, no exotic mass peak is observed. The number of $pK^0_s$ produced at 1540 MeV in a narrow resonance is less than 0.5% of the observed number of $\Lambda(1520) \rightarrow pK^-$.

Hence, we conclude that the production of pentaquark resonances is heavily suppressed with respect to the production of normal baryon and antibaryon resonances in $pp \rightarrow pX$ at 800 GeV/c.
Figure 5. $pK_s$ and $pK^-$ invariant mass distributions below 1.7 GeV/c$^2$ for events in reaction (7).

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