Search for $\Theta^+$ and $\Xi^{−3/2}$ pentaquarks in HERA-B

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Abstract. A search for $\Theta^+(1540)$ and $\Xi^{−3/2}(1860)$ pentaquark candidates has been performed in proton-induced reactions on C, Ti and W targets at $\sqrt{s} = 41.6$ GeV studying the $pK^0$ resp. $Ξ^−\pi^−$ and $Ξ^−\pi^+$ (and charge conjugated (c.c.)) decay channels at mid-rapidity. With sensitivities of $\text{Br} \times d\sigma/dx < 5$ to $25 \mu b$/nucleon, we find no evidence for narrow pentaquark peaks in any of the studied final states. Preliminary values for the upper limit of relative yield ratios at mid-rapidity are $\text{Br} \times \Theta^+(1540)/\Lambda(1520) < 0.02$, $\text{Br} \times \Xi^{−3/2}(1862)/\Xi(1530)^0 < 0.077$, and $\text{Br} \times \bar{\Xi}^{++3/2}(1862)/\bar{\Xi}(1530)$ at $95\%$ CL.

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1. Introduction

Recently, evidence for an exotic $S = +1$ baryon has been reported by several experiments using incident beams of real and quasi-real photons, kaons, and (anti-)neutrinos [1]. With a significance of 4.4 to 7$\sigma$, they find in the $pK^0_S$ or $nK^+$ channels a resonance with a mass between 1526 and 1542 MeV/$c^2$ and with a width of typically $< 20$ MeV dominated by the experimental resolutions. Best constraints on width come from a re-analysis of kaon scattering and exclude a value larger than 5 MeV/$c^2$ [2]. This new state is tentatively identified with the $\Theta^+$ pentaquark ($uudd\bar{s})$ baryon, which has been predicted [3] within a chiral soliton model to reside at 1530 MeV/$c^2$, to have a width of less than 15 MeV/$c^2$, and to decay into the KN channels. Other model interpretations including correlated quark pairs are discussed in [4]. The $\Theta^+$ is member of an antidecuplet exhibiting two further exotic states, the $\Xi^{+3/2}(ddss\bar{u})$ and the $\Xi^{−3/2}(uuss\bar{d})$. A candidate for the $\Xi^{−3/2}$ has been found by the NA49 collaboration in the $\Xi^−\pi^−$ channel at 1862 MeV/$c^2$ with a width of less than 18 MeV/$c^2$ [5]. At the same mass, evidence for a new resonance is also seen in the $\Xi^−\pi^++$ c.c. channels. For establishing the existence and character of the new resonances beyond any doubt, high statistics mass spectra and the measurements of spin, parity, width and cross sections are needed. Exploring the production mechanism of pentaquark states can lead to a better understanding of non-perturbative QCD, and relative particle yields like $\Theta^+/\Lambda$ or $\Theta^+/(1520)$ can provide new insight in the dynamics of production mechanisms. Statistical hadronization models predict these ratios to be >0.02 resp. >0.4 and energy-dependent [6, 7, 8]. Taking advantage of a huge sample of minimum
bias data from proton-nucleus collisions, HERA-B can considerably contribute to all these topics.

2. Experiment and data sample

HERA-B is a fixed target experiment at the 920 GeV proton storage ring of DESY. It is a forward magnetic spectrometer with a large acceptance, a high-resolution vertexing and tracking system and good particle identification [9]. The present study uses a sample of more than 200 million minimum bias events which was taken at mid-rapidity ($x_F \sim 0$) on carbon, titanium and tungsten targets during the 2002/03 run period. For this analysis the information from the silicon vertex detector, the main tracking system and the ring-imaging Cherenkov counter (RICH) was used. With standard techniques described in [9], signals from $K^0_S \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ decays can be identified above small backgrounds (Figure 1a,b,c). Similar clean signals from $\Xi^-$ $\rightarrow \Lambda \pi^-$ and c.c. decays (Figure 1d) are obtained by requesting that none of the decay products but only the $\Xi^-$ itself must point to the primary vertex. The measured mass resolutions for $K^0_S$, $\Lambda$ and $\Xi^-$ ($\Xi^+$) signals of 4.9 MeV, 1.6 MeV, and 2.6 MeV are about 20% larger than the values from Monte Carlo simulations. The number of observed $K^0_S$, $\Lambda+\bar{\Lambda}$ and $\Xi^-+\Xi^+$ events totals about $3.4 \times 10^6$, $1.4 \times 10^5$, and $1.9 \times 10^4$, respectively.

3. Search for $\Theta^+ \rightarrow p + K^0_S$ decays

The large statistics of $K^0_S$ events allows to apply very strict criteria for proton identification by the RICH. The cut in the proton likelihood of $>0.95$ implies that the probability to identify other particles with momenta between 20 and 55 GeV/c as protons is less than 3%. In the $K^0_S$ sample the $\Lambda$ and $\bar{\Lambda}$ contaminations were removed [10]. In addition, only $pK^0_S$ pairs from events with an identified primary vertex were accepted. The invariant mass spectrum of the $pK^0_S$ pairs is shown in Figure 2a) for the p+C data. The spectrum exhibits a smooth shape without any narrow structure. The solid line represents the background determined from event mixing. In the background-subtracted spectrum (Figure 2b), the data points scatter around zero showing again no evidence for a narrow structure in the mass region between 1450 and 1700 MeV/c$^2$. 

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Signals from decays of a) $K^0_S \rightarrow \pi^+\pi^-$, b) $\Lambda \rightarrow p\pi^-$, c) $\bar{\Lambda} \rightarrow \bar{p}\pi^+$, d) $\Xi^- \rightarrow \Lambda \pi^-$ and $\Xi^+ \rightarrow \bar{\Lambda} \pi^+$, and e) $\Lambda(1520) \rightarrow pK^-$. $\Delta m=1.0/0.4$ MeV/c$^2$ in a)/b),c).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Counts of a) $K^0_S \rightarrow \pi^+\pi^-$, b) $\Lambda \rightarrow p\pi^-$, c) $\bar{\Lambda} \rightarrow \bar{p}\pi^+$, d) $\Xi^- \rightarrow \Lambda \pi^-$ and $\Xi^+ \rightarrow \bar{\Lambda} \pi^+$, and e) $\Lambda(1520) \rightarrow pK^-$. $\Delta m=1.0/0.4$ MeV/c$^2$ in a)/b),c).}
\end{figure}
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From Monte-Carlo simulations, the experimental mass resolution for a $\Theta^+$ is found to be $\sigma \sim 3.8$ MeV/$c^2$. The estimated sensitivity $Br\times d\sigma/dx_F$ for a narrow signal is about 5 $\mu$b / nucleon assuming the cross section to scale with $A^{0.7}$. Also other search strategies did not yield a significant narrow structure around 1540 MeV/$c^2$ including i) a cut in the track multiplicity of the event (Figure 2c), ii) the request for the presence of a tagging particle like $\Lambda$, $\Sigma$ or $K^-$ in the event, or iii) both conditions (Figure 2d), and iv) the relaxation of the proton momentum cut implied by the RICH PID. With the same proton PID used for the pK$_S^0$ pairs, the combination of protons with $K^-$ particles yields a clean signal of the $\Lambda(1520) \rightarrow pK^-$ decay (Figure 1e) proving the PID performance. In fact, $\Theta^+ \rightarrow pK_S^0$ and $\Lambda(1520) \rightarrow pK^-$ decays exhibit a very similar geometrical acceptance and, assuming a branching ratio of 0.25 of the $\Theta^+$ into the pK$_S^0$ channel, a preliminary value for the upper limit of the relative particle yield $\Theta^+ / \Lambda(1520)$ at mid-rapidity is 0.02 at 95% CL. This value is significantly lower than the statistical hadronization model prediction of 0.57 for p-p collisions at $\sqrt{s} = 17$ GeV.

4. Search for $\Xi^{-3/2} \rightarrow \Xi^- + \pi^-$ decays

Like in the NA49 study 5, resonances were searched for in both the doubly-charged $\Xi^- \pi^-$ and in the neutral $\Xi^- \pi^+$ channels. $\Xi$ candidates with a mass of ±10 MeV/$c^2$ of the table mass were accepted. Figure 3 shows the corresponding invariant mass spectra and the backgrounds determined by event mixing. In the neutral decay channels, (Figure 3a), the $\Xi(1530)^0$ resonance shows up with a prominent signal, and there is a possible weak evidence for known higher $\Xi^*$ resonances. In the doubly-charged channels (Figure 3b), the background follows very well the data, and, in particular, there is no evidence for a narrow signal at around 1862 MeV/$c^2$ at a sensitivity of $Br\times d\sigma/dx_F|_{x_F=0} < 25$ $\mu$b / nucleon. The preliminary values for the two upper limits of the relative production yields $Br \times \Xi^{-3/2}(1862)/\Xi(1530)^0$ and $Br \times \Xi^{+3/2}(1862)/\Xi(1530)^0$ at mid-rapidity are 0.077 and 0.058 at 95% CL, respectively.

\begin{figure}[h]
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\includegraphics[width=\textwidth]{figure2.png}
\caption{The pK$_S^0$ invariant mass distributions: a) data from the p+C collisions with background (continuous line) determined from event mixing; b) as a) but with the background subtracted; c) as a) but requiring a track multiplicity of < 10. d) data from all targets C, Ti, W requiring a track multiplicity of < 20 and a $\Lambda$ particle in the event. Arrows mark the mass of 1540 MeV/$c^2$.}
\end{figure}
5. Conclusions

The present study exploited a high statistics minimum bias sample obtained from central proton nucleus collisions at $\sqrt{s} = 41.6$ GeV and the high momentum resolution of the HERA-B spectrometer for a sensitive search of narrow pentaquark signals. The performance of the analysis technique has been verified by the reconstruction of clear $\Lambda(1520) \to pK^-$ and $\Xi(1530)^0 \to \Xi^-\pi^+$ signals. No evidence is found, however, for narrow signals from the $\Theta^+$ around 1540 MeV/$c^2$ or the $\Xi^{--}_{3/2}$ candidate at about 1862 MeV/$c^2$ in the $pK_S^0$ and $\Xi^-\pi^-$ channels, respectively. The sensitivity to identify a $\Theta^+$ signal in the $pK_S^0$ channel is estimated to be better than $5 \mu b$ / nucleon. More systematic studies and the evaluation of cross section limits are in progress. The relative particle yield $\Theta^+/\Lambda(1520)$ of less than 0.02 (95% CL) at mid-rapidity is not compatible with the predictions of the statistical hadronization model [8]. If existent, pentaquarks seem to exhibit also exotic production mechanisms.

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