Search for the $\Theta^{-} \to K^{-}\bar{n}$ with PHENIX

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Abstract. The PHENIX experiment at RHIC should be sensitive to decays of the anti-pentaquark $\Theta^{-}$ via the $K^{-}\bar{n}$ channel. Charged kaons can be identified using the standard tracking and time of flight up to a momentum of 1.5 GeV/c. Anti-neutron candidates are detected via their annihilation signal in the highly segmented electromagnetic calorimeter (EMCal). In order to assess the quality of the anti-neutron identification we reconstruct the $\Sigma \to n\pi$. As an additional crosscheck the invariant mass of $K^{+}\bar{n}$ is reconstructed where no resonance in the pentaquark mass range is expected. At the present time no enhancement at the expected pentaquark mass is observed in dAu collisions at $\sqrt{s_{NN}} = 200$ GeV.

The possibility of five quark systems (pentaquarks) has been discussed for more than two decades (see, e.g. Ref [1]). A recent publication [2] based on the soliton model made a prediction of a narrow resonance ($\Gamma < 15$ MeV/$c^2$) with a mass $\approx 1530$ MeV/$c^2$. This pentaquark -- designated the $\Theta^{+}$ -- is expected to decay into the channels $K^{+}n$ and $K^{0}p$. Starting in 2003 narrow resonances in the expected mass range have been observed in many experiments (LEPS [3], DIANA [4], CLAS [5] [6], SAPHIR [7], HERMES [8], SVD [9], COSY-TOF [10]). A peak was also found in neutrino scattering experiments [11].

The reconstruction of the $\Theta^{+}$ pentaquark is technically difficult in PHENIX [12], due to the relatively small acceptance for 3-body final states and the difficulty of detecting neutrons. However, due to the unique signature of anti-neutrons in the highly segmented PHENIX electromagnetic calorimeter, a search for decays of the anti-pentaquark $\Theta^{-} \to K^{-}\bar{n}$ is technically feasible.

Charged particles are tracked using the central arm spectrometers [13]. The kaon identification is accomplished by combining their momentum obtained from the tracking detectors with their time-of-flight as measured by the EMCal, shown in fig.1. The upper limit of the momenta for separating kaons is 1.5 GeV/c, beyond which the contamination by pions becomes too large.

The anti-neutron candidates are selected via their annihilation signal in the EMCal. Since there is no independent measurement of anti-neutrons to calibrate the EMCal response, guidance for identifying the anti-neutron signal is provided.

§ For the full PHENIX Collaboration author list and acknowledgments, see Appendix “Collaborations” of this volume.
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**Figure 1.** Charged kaon identification: The momentum is reconstructed by the central tracking, the time-of-flight is determined by the EMCal. The range of identified kaons is marked in black.

**Figure 2.** EMCal response for protons and anti–protons. The additional annihilation energy of the anti–protons leads to larger clusters. Searching for large clusters is the main tool to identify anti–neutron candidates by the characteristics of clusters created by identified protons and anti–protons. The identification of both protons and anti–protons is accomplished via the usual combination of momentum and time-of-flight, and the resulting sample is used to determine the features of the annihilation signal in the calorimeter. The main differences in the response of the EMCal to protons and anti–protons are the number of struck towers and the amount of energy deposited, as shown in fig.2. Only clusters with a measured time more than 3 ns later than the photon arrival time were used in the analysis, and further, clusters were only used if the shower shape showed a poor fit to that expected for a photon.

To remove clusters which were produced by charged particles a layer of pad chambers (PC3) in front of the EMCal was used as a veto counter. Clusters within 12 cm of a PC3 hit were excluded. In order to compensate for dead regions of the PC3, EMCal clusters which are closer than 12 cm to the trajectory of a charged track at the EMCal surface were also removed.

The selected anti–neutron candidates are then combined with identified charged kaons (and pions for the reconstruction of $\Sigma$ baryons) and the invariant mass of these pairs is calculated. To subtract the uncorrelated background a high statistics distribution using pairs from mixed events is created. The reconstruction of anti–sigmas provides an important confirmation of the validity of these techniques. As shown in fig.3.
the $\pi^+\pi^-$ invariant mass distribution exhibits a peak very close to the nominal mass of the $\Sigma^-$ (1.197 GeV/$c^2$ [14]). Future PHENIX limits or yields for anti–pentaquark production at RHIC are likely to rely on this observation as an important calibration of both experimental resolution and acceptance for anti–neutrons.

A further crosscheck for a real anti–pentaquark signal is the absence of a signal in the invariant mass distribution of K$^+\pi^-$ which is shown in fig. 4. No resonance is expected in the mass range of 1.5GeV/$c^2$ – 1.6GeV/$c^2$ but technical problems and contaminations due to misidentified particles should affect both distributions.

The analysis was done with d + Au data at $\sqrt{s_{NN}} = 200$ GeV which were taken during Run-3 at RHIC. In the initial analysis of peripheral events (Centrality>30% of the inelastic cross section) a statistically significant peak at an invariant mass of 1.54 GeV/$c^2$ was observed but no peak was seen in the accompanying K$^+\pi^-$ invariant mass distribution. This was the status of the analysis which was reported at the conference. As part of a systematic investigation of this intriguing result, an independent analysis was performed which showed no structure in the vicinity of 1.54 GeV/$c^2$. 

Figure 3. $\pi^+\pi^-$ Invariant mass distribution. The peak is very close to the expected value of 1.197 GeV/$c^2$. The lower panel shows the distribution after the mixed background is subtracted. This plot contains the timing correction. Without the timing correction the width of the peak is about a factor of 2 larger.

Figure 4. K$^+\pi^-$ Invariant mass distribution. No peak is expected in the mass range between 1.5 GeV/$c^2$ and 1.6 GeV/$c^2$. It serves as a crosscheck for technical problems and particle misidentifications.
Further comparisons determined that the original analysis lacked a necessary timing correction. This translated into a distortion of the momentum of only the anti–neutrons. The correction is negligible (<5%) for most of the events, which is the reason why the original analysis could reconstruct the \( \Sigma \). However, as a result of applying the correction the peak at 1.54 GeV/c\(^2\) in the \( K^-\pi^-\) invariant mass distribution loses its statistical significance. The distribution shown in fig. 5 uses the same events and the same cuts as those originally presented, but after application of the correction. The \( K^+\pi^-\) invariant mass distribution in fig. 4 (also after application of the correction) which served as a safeguard against technical problems and particle misidentifications did not change visibly.

Currently it is unclear what mechanism is behind the appearance of the peak at 1.54 GeV/c\(^2\) and why the control \( K^+\pi^-\) invariant mass distribution did not exhibit the same feature. This is being actively investigated. The unique anti–neutron capabilities of the PHENIX apparatus, as evidenced by the cleanly reconstructed anti–sigma channel, leave open the possibility of testing of coalescence models for their production\[16, 15\] by establishing limits or measuring yields of anti–pentaquarks at RHIC.

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