Pentaquark Search in Relativistic Heavy Ion Collisions with STAR

Sevil Salur
(for the STAR Collaboration)

Yale University
Physics Department, 272 Whitney Ave.
New Haven, CT 06520

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We report on the progress of the pentaquark searches by the STAR collaboration in p+p, d+Au, and Au+Au at \( s_{NN} = \sqrt{200} \text{ GeV} \) collisions through one of the decay modes of \( \Theta^+ \rightarrow p + K^0_s \). \( \Theta^+ \) state is an exotic baryon with strangeness \( S = 1 \) and is the lightest isospin member of the expected antidecuplet. We compare our techniques for the pentaquark search with those for the short-lived resonances. These results were presented as a poster at Quark Matter 2004.

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I. INTRODUCTION

The first observations of the \( \Theta^+ \) pentaquark, a five quark bound system of uuudS, have been reported in photon-nucleus and kaon-nucleus reactions \(^1\)\(^2\)\(^3\). The presence of this state was predicted by R. Jaffe with multiquark bag models \(^4\)\(^5\) and later by D. Diakonov et al. using chiral soliton models of baryons \(^6\).

The high energies and particle densities resulting from collisions at the Relativistic Heavy Ion Collider (RHIC) are expected to favor pentaquark production. The data that we analyze were taken by the STAR (Solenoidal Tracker At RHIC) experiment, one of the four relativistic heavy ion experiments at RHIC. The large acceptance of STAR’s Time Projection Chamber (TPC) is ideal for such rare particle searches. The short lifetimes predicted for pentaquarks require that a mixing technique be used to reconstruct pentaquarks via their decay products. This technique has already been used successfully by STAR to reconstruct and study resonances \(^7\)\(^8\).

II. ANALYSIS AND PARTICLE IDENTIFICATION

Charged daughter particles are identified by the momentum and the energy lost per unit length, \( dE/dx \), measured with the Time Projection Chamber of STAR. For long lived particles (\( cT \sim \text{few cm} \)) such as \( K^0_s \), \( \Lambda \) and \( \Xi \), the decay vertex topology information is used for their identification. This method cannot be used for pentaquarks since they decay strongly (\( cT \sim \text{fm} \)). An alternative method, a mixing technique, is used successfully to identify short lived particles such as resonances (\( cT_{\Sigma(1385)} = 5 \text{ fm} \)) and can be used to search for pentaquarks and dibaryons.

In the mixing technique, for example \( \Sigma(1385) \rightarrow \Lambda + \pi \), we identify first the \( \Lambda \)’s by their decay vertex topology, due to their long lifetime (\( cT_\Lambda = 7.89 \text{ cm} \)). This \( \Lambda \) candidate is then combined with a \( \pi \) to get \( \Sigma(1385) \). The background is described by combining \( \pi \)’s from one event with the \( \Lambda \)’s from another event. Similarly for pentaquarks such as \( \Theta^+ \rightarrow K^0_s + p \), we first identify the \( K^0_s \) via its decay vertex topology and then combine this \( K^0_s \) candidate with a proton candidate in the same event to extract the signal and in a different event to describe the mixing background.

III. STATUS OF CURRENT STUDIES

A. Monte Carlo Studies

To study the decay mechanism and optimize the applied cuts, we use Monte Carlo simulations. In this study, one Monte Carlo \( \Theta^+ \) pentaquark is chosen from a thermal exponential distribution with \( T_{\text{invelope}} = 250 \text{ MeV} \) for a rapidity \( |y| < 1.5 \) and is embedded in a single real p+p event after a full TPC simulation. The chosen input width, 10 \( \text{MeV/c}^2 \), and the input mass, 1.54 \( \text{GeV/c}^2 \), are consistent with the observed mass and width of \( \Theta^+ \).

FIG. 1: Invariant mass spectrum of the simulated Monte Carlo input for the \( \Theta^+ \) and \( p_T \) vs rapidity of the \( \Theta^+ \) that can be identified with the TPC.
In Fig. 1 the invariant mass spectrum of simulated $\Theta^+$ and the TPC acceptance for the corresponding simulated particles can be found. In Fig. 2 the invariant mass spectrum of the reconstructed $\Theta^+$ are presented. We find that $\sim 3\%$ of these Monte Carlo $\Theta^+$’s are successfully reconstructed with this technique. The reconstructed width and the mass is consistent with the Monte Carlo input. We can study the decay properties with the simulated tracks such as the momentum distribution of the decay daughters. Fig. 3 and Fig. 4 are the momentum distributions of the $K^0_s$ and $p$ respectively. With this study we can apply momentum cuts to increase the signal-to-background ratio. This ratio can be increased clearly by selecting protons with momentum less than 1 GeV/c. Further detailed studies on other variables are needed to optimize the signal-to-background ratio.

B. Mixing Technique Works

$\Sigma(1385) \rightarrow \Lambda + \pi_{bachelor}$ is identified in p+p, d+Au, and Au+Au collisions with the mixing techniques. Fig. 3 and Fig. 4 are the preliminary, background subtracted invariant mass spectra of the $\Sigma \rightarrow \Lambda + \pi$ and $\Sigma(1385) \rightarrow \Lambda + \pi$ for p+p and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

FIG. 2: Invariant mass spectrum of the Monte Carlo simulated $\Theta^+$ embedded in real p+p events with the mixing technique. Black solid line is the signal and red dashed line is the mixed event background. The simulated signal can be clearly seen.

FIG. 3: $K^0_s$ momentum distribution: Black solid line is of the accepted $K^0_s$ after the topological cuts and red dashed line is of the decay daughters of the Monte Carlo simulated $\Theta^+$ for the same number of events.

FIG. 4: Proton momentum distribution: Black solid line is of the accepted p after the dE/dx cut and red dashed line is of the decay daughters of the Monte Carlo simulated $\Theta^+$ for the same number of events.

FIG. 5: Background subtracted invariant mass spectrum of $\Sigma(1385)$ in p+p collisions.

FIG. 6: Background subtracted invariant mass spectrum of $\Sigma(1385)$ in d+Au collisions.

In these figures the invariant mass spectra of $\Sigma(1385)^+$, $\Sigma(1385)^-$ and their antiparticles are summed to improve the statistics. Similarly Fig. 4 is for the Au+Au central collisions. For this figure only $\Sigma(1385)^+$ and $\Sigma(1385)^-$ are added.

The $\Xi$ peaks are fit with gaussian distributions and the $\Sigma(1385)$ peaks are fit with a Breit-Wigner distribution. Antiparticle-to-particle ratios of $\Xi$ and $\Sigma(1385)$ are observed as $0.89 \pm 0.04$ and $0.90 \pm 0.07$ respectively in p+p collisions. (In addition to the given statistical errors, these ratios also have a 20% systematic error due to the mixed event background normalization.) These values are consistent with what we observe for other hadronic events.
particle ratios at RHIC in p+p collisions, such as the antiproton to proton ratio which is $p/p \sim 0.8$. We expect a similar production of pentaquarks and their antiparticles at RHIC. A very preliminary invariant mass spectrum of the $\Theta^+$ in p+p collisions is shown Figure 8. Further studies are needed to optimize the signal-to-background as no strong signal is observed. The invariant mass spectrum that we observe for the $\Theta^+$ in p+p collision events is consistent with our predictions for the significance of the signal given our current statistics. Details can be found in the selection of events and applied cuts. To improve cuts and understand the decay mechanism we can do more detailed simulation studies. For Au+Au and d+Au collisions similar invariant mass spectra are observed.

C. Feasibility Studies

Assuming the $\Theta^+$ production is $10 - 100\%$ of the $\Lambda(1520)$ in p+p collisions, one can predict the yield of $\Theta^+$. Preliminary $dN/dy$ of $\Lambda(1520)$ at mid-rapidity is 0.004 per event in p+p collisions [12, 13]. There are 8 Million p+p events available for this analysis. This corresponds to a production of $\sim 30000 \Lambda(1520)$ and a production range of $\sim 3000$ to $\sim 30000 \Theta^+$’s in these p+p events. As the efficiency of the mixing technique is $\sim 3\%$ and the branching ratio of the $\Theta \rightarrow K^0 + p$ is $\sim 25\%$ (assuming that the branching ratios of $\Theta \rightarrow K^0 + p$ and $\Theta \rightarrow K^+ + N$ are 50\% each), 20-200 of the $\Theta$’s can be found with the mixing technique. The background pairs per event in the 1.54±5 MeV mass range is 3200. This corresponds to a significance of 0.25 to 3 for the significance defined as $\frac{\text{Signal}}{\sqrt{2 \times \text{Background} + \text{Signal}}}$. Similarly one can repeat the same study for Au+Au and d+Au collisions and correspondingly predict a significance of 2-7 for 1.5 Million Au+Au events and 1-16 for 10 Million d+Au for the predicted production of one $\Theta^+$ per rapidity per collision [9, 10, 11]. To estimate the yield for the d+Au collisions we assume $N_{\text{part}}$ scaling. The mean number of participants in d+Au is 8, in p+p it is 2, and in Au+Au it is 350 for the most central collisions. The lower limit is obtained from p+p scaling while the upper limit is from Au+Au yield estimates.

IV. CONCLUSION

Preliminary acceptance and efficiency studies show that we should be able to find pentaquarks at the few \% level. Resonances can be clearly reconstructed via event mixing techniques in p+p, d+Au and Au+Au central collisions. Optimization of cuts to improve the signal over background is in progress. There is a possibility of measuring the anti-pentaquarks at RHIC since the antibaryon to baryon ratio indicates a nearly net baryon free region [14]. 100 Million events for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV are planned to be collected in 2004, Run 4, which has just started. This would be 70 times the currently available data. The predicted significance of identifying $\Theta^+$ is at a range of 20 to 84 with the forthcoming data. We expect to put a more definite upper limit to the yields and production mechanisms of the pentaquarks in Au+Au collisions with the 2004 run which will finish collecting data at the end of May 2004.
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