Σ(1385) Results and Status of the Θ+ in STAR

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Abstract. The Σ(1385) analysis and the current status of pentaquark search with the STAR detector are reported. The corrected $p_T$ spectra and the yields of the $Σ^\pm (1385)$ and their antiparticles in the most central Au+Au as well as elementary $p+p$ collisions are presented. A comparison of the $⟨p_T⟩$ of observed particles suggests a similar behavior for particles with mass greater than 1.2 GeV in $p+p$ and Au+Au collision environments. Acceptance and efficiency studies with simulations show that the (anti)pentaquarks should be found at the 3 % level.

1. Introduction

The observation of a five-quark bound system consisting of uudds, referred to as the Θ+ pentaquark, have been reported in photon-nucleus and kaon-nucleus reactions [1, 2, 3]. The presence of this state was predicted by R. L. 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 be ideal environments for pentaquark production [7, 8, 9, 10].

During the expansion of the hot and dense matter (fireball) created in Au+Au collisions, chemical freeze-out is reached when the hadrons stop interacting inelastically. Elastic interactions continue until thermal freeze-out. Due to the very short lifetime ($τ < τ_{fireball}$) of resonances, a large fraction of the decays occur during this time. The elastic interactions of decay products with the surrounding particles result in a signal loss in the particle identification though this is offset by secondary interactions which increase the resonance yield (e.g. $Λ + π → Σ(1385)$, $K+p → Θ^+$). The contribution of re-scattering and regeneration on the total observed yields depends on the time span between the chemical and thermal freeze-out and the lifetime of each resonances [11, 12]. Thus the study of resonances provides an additional tool in the determination of the hadronic expansion time between chemical and thermal freeze-out by comparing resonance to stable particle ratios. The data analyzed were taken by the STAR (Solenoidal Tracker At RHIC) experiment[13], one of the four experiments at

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RHIC. The large acceptance of STAR’s Time Projection Chamber (TPC) is ideal for such rare particle searches.

2. Particle Identification

The STAR trigger detectors consist of two zero degree calorimeters (ZDCs) which are situated $\sim 17$ m downstream of the nominal interaction point as well as a central trigger barrel (CTB) surrounding the TPC. A minimum bias trigger is defined by the coincident measurement of spectator neutrons in both ZDCs. The CTB an array of scintillator slats, is used to detect event multiplicity, is used to trigger on the 10% most central Au+Au collisions. For p+p collisions, a minimum bias trigger is defined by coincidences in the two beam-beam counters, which are again scintillator detectors and are situated around the beam pipe, approximately 2 m from the center of the TPC. The main detector component of STAR is the TPC, which, together with the magnetic field information, is used to identify stable charged particles via energy loss per unit length and long-lived weakly decaying ($cT \sim \text{few cm}$) neutral particles such as $\Lambda$ and $K^0_S$ via their decay topology. The direct measurement of resonances is not possible due to their short lifetimes ($cT_{\Sigma(1385)} = 5 \text{ fm}$) [14, 15]. Instead, $\Sigma(1385)$ resonances are identified by the invariant mass after combining $\pi$ with $\Lambda$ decay particle candidates. A mixed event technique, where particles from different events are reconstructed using the same technique, is used to determine the background for uncorrelated pair combinations. The $\Sigma(1385)$ signal is obtained by the subtraction of this normalized mixed event background from the invariant mass distribution [16]. This technique can directly be applied for the search and possible identification of pentaquarks. For the case of the $\Theta^+$ pentaquark study the invariant mass reconstruction is via $\Theta^+ \rightarrow K^0_S + p$, and subtraction of the normalized mixed event background is used [18].

3. The $\Sigma(1385)$ Analysis

The transverse mass ($m_T = \sqrt{p_T^2 + m^2}$) spectra of $\Sigma^{\pm}(1385)$ and their antiparticles in p+p (circles) and Au+Au (stars) collisions are shown in Fig. 1. The spectra are corrected for acceptance and efficiency by embedding Monte-Carlo simulated resonances into real p+p and Au+Au events. The solid lines in Fig. 1 represent exponential fits to the data with the function directly proportional to the yield (dN/dy) and inversely proportional to temperature ($T^2 + m_0 T$). The data coverage is 91% in p+p and 85% in Au+Au collisions of the fully integrated yield. The $\langle p_T \rangle$ is derived from the full range integration of the corresponding exponential fit. Table 1 presents the inverse slope parameter ($T$), the $\langle p_T \rangle$ and the yield (dN/dy) for the summed signal of $\Sigma^{\pm}(1385)$ together with their antiparticles, for both p+p and Au+Au collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$.

The $\langle p_T \rangle$ for various particles in both p+p and Au+Au collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$ as a function of their mass are presented in Fig. 2. The behavior of $\langle p_T \rangle$.
The transverse mass spectrum for $\Sigma(1385)$ drawn as stars for the $0-5\%$ most central Au+Au and circles for p+p collisions at $\sqrt{s_{NN}} = 200$ GeV. Blue circles are for p+p and red stars are for Au+Au collisions.

vs. mass for the various particles in p+p and Au+Au collisions is compared to two parameterizations. The black curve is an empirical fit to the ISR $\pi$, $K$ and $p$ data [19] and the shaded band is a blast wave fit using $\pi$, $K$ and $p$ data in Au+Au collision system [17]. The empirical parametrization for the ISR data at $\sqrt{s} = 25$ GeV in p+p collisions, can describe the behavior of the lower mass particles, such as $\pi$, $K$ and $p$, despite the fact that our collision energy is one order of magnitude higher. However, this empirical parametrization does not represent the behavior of the higher mass particles. Similarly, the blast wave parametrization which can describe the lower mass particles in Au+Au collisions ($\sim 98\%$ of all the particles observed) fails to explain the behavior of higher mass particles.

The comparison of lighter, weakly decaying particles and heavier resonances in p+p and Au+Au collision environments shows a similar behavior of $\langle p_T \rangle$ for the higher

| $\Sigma^\pm(1385)$ in p+p | T [MeV] | $\langle p_T \rangle$ [GeV/\text{c}] | Yields (dN/dy) |
|--------------------------|---------|----------------------------------|----------------|
|                          | 358 ± 47 | 1.08 ± 0.15                     | $(4.66 \pm 0.98) \times 10^{-3}$ |
| $\Sigma^\pm(1385)$ in Au+Au | 420 ± 84 | 1.20 ± 0.24                     | 4.72 ± 1.38    |

Table 1. Temperature T, $\langle p_T \rangle$ and yield obtained from the exponential fits of the $p_T$ spectra in Fig. 1 for elementary p+p and 0-5% most central collisions. The statistical uncertainties are given and the systematical error due to normalization of the background, $\sim 15\%$, has to be included in the given values.
mass particles. It is expected that resonances with higher transverse momentum are more likely to be reconstructed in Au+Au collisions because of their longer relative lifetimes due to Lorentz contraction. This means they are more likely to decay outside the medium and hence their daughter particles would interact less with the medium. Any loss at low $p_T$ would increase the $T$ parameter of the $p_T$ spectra for the central Au+Au collisions with respect to p+p collisions. However we do not see any significant increase in the $T$ parameter for $\Sigma(1385)$ from p+p to the most central Au+Au collisions within the statistical and systematic errors. If higher mass particles are produced by different production mechanisms than the lower mass particles, we might be introducing a bias in our measurement in p+p collisions. This may be due to a number of reasons which include higher mass particles being produced in more violent (mini-jet) p+p collisions and/or the heavier particles flow radially with a smaller velocity than the lighter mass particles (such as $\pi$ mesons) in the most central Au+Au collisions. The $\langle p_T \rangle$ measurement of the higher mass resonance $\Sigma(1385)$ shows this merging behavior. Similarly the study of radial flow of heavier particles can give us valuable information about whether the heavier particles flow less with respect to lower mass particles.

A comparison of $\Sigma(1385)/\Lambda$ ratios in p+p and 0 – 5% central Au+Au collisions shows no suppression from p+p to Au+Au. An observed suppression of $K^*(892)/K$...
and $\Lambda^*(1520)/\Lambda$ ratios in Au+Au collisions with respect to p+p collisions suggests a signal loss via re-scattering in the medium by thermal models [20, 21]. As the lifetime of a $\Sigma(1385)$ is one third that of the $\Lambda^*(1520)$, it is expected that there should be an even greater signal loss via re-scattering. The observed unsuppressed ratio requires a significant regeneration mechanism in order to recover the signal loss via re-scattering. The measured $\Sigma^+(1385)/\Lambda$ ratio is $0.295 \pm 0.086$ for the 0-5% most central collisions which is about a factor of 2 below the microscopic model UrQMD predictions at $\sqrt{s_{NN}} = 200$ GeV. This suggests that the assumed regeneration cross-section, included in UrQMD calculations, is too high [22]. Both UrQMD and thermal production models should be revised in light of the resonance measurements.

4. Status of Current $\Theta^+$ Studies

4.1. Monte Carlo Studies

To study the decay mechanism and optimize the applied cuts, Monte Carlo simulations are used. In this study, one Monte Carlo $\Theta^+$ pentaquark is chosen from a thermal exponential distribution with $T = 250$ MeV in the rapidity interval $|y| < 1.5$ and after a full TPC simulation is embedded into a single, real p+p event. The chosen input width, 10 MeV/$c^2$, and the input mass, 1.54 GeV/$c^2$, are consistent with the observed mass and width of $\Theta^+$ [1, 2, 3]. In Fig. 3 the invariant mass spectrum of the reconstructed $\Theta^+$ is presented. We find that $\sim 3\%$ of these Monte Carlo generated $\Theta^+$’s are successfully reconstructed with this technique. The reconstructed width and the mass is consistent with the Monte Carlo input.

Using this technique, the decay properties with the simulated tracks such as the momentum distribution of the decay daughters can be studied. In Fig. 4, the momentum
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The momentum distributions of $K_S^0$ and protons from Monte Carlo generated $\Theta^+$ decay are shown in Figure 4. The black solid histograms represent the accepted $K_S^0$ on the left and protons on the right after the dE/dx cuts, while the red dashed histograms represent the decay daughters of the Monte Carlo generated $\Theta^+$ for the same number of events. With this study, we can optimize momentum cuts to increase the signal-to-background ratio. Clearly, an optimized cut to improve this ratio is to accept protons with momentum less than 1 GeV/c while at the same time rejecting the ones above this threshold. Further detailed studies on other variables are needed to optimize the signal-to-background ratio.

4.2. Feasibility Studies

Assuming that the $\Theta^+$ production is $10 \text{--} 100\%$ of the $\Lambda^*(1520)$ in p+p collisions, one can estimate the yield of the $\Theta^+$. The preliminary $dN/dy$ of $\Lambda^*(1520)$ at mid-rapidity is 0.004 per event in p+p collisions [23, 24]. There are 8 Million p+p events available for this analysis and this corresponds to a production of $\sim 30000 \Lambda^*(1520)$, giving a production range of $\sim 3000$ to $\sim 30000$ $\Theta^+$’s in these p+p events using the above estimates. As the efficiency of the mixing technique is $\sim 3\%$ and the branching ratio of $\Theta^+ \rightarrow K_S^0 + p$ is $\sim 25\%$ (assuming that the branching ratios of $\Theta \rightarrow K_S^0 + p$ and $\Theta^+ \rightarrow K^+ + N$ are each 50%), 20-200 of the $\Theta^+$’s should be found. The background pairs per event in the $1.54 \pm 5 \text{ MeV}$ mass range is 3200. This corresponds to a significance of between 0.25 and 3.‡ 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 unit rapidity per collision [7, 8, 9, 10]. To estimate the yield for the d+Au collisions we assume scaling with the number of participants ($N_{part}$). 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. The invariant mass spectra that are observed for the $\Theta^+$ in p+p, d+Au and Au+Au collision events are consistent with our estimations for the significance of the signal given our

‡ The significance is defined as $\frac{\text{Signal}}{\sqrt{2 \times \text{Background} + \text{Signal}}}$.
current statistics. The signal-to-background ratio depends highly on the selection of events and applied cuts. To improve cuts and understand the decay mechanism more detailed simulation studies must be undertaken.

5. Conclusions

Σ±(1385) resonances and their antiparticles can be reconstructed via event mixing techniques in p+p, d+Au and Au+Au collision environments with STAR. The Σ(1385) ⟨pT⟩ in p+p collisions is similar within the errors to that measured in Au+Au collisions. This follows the behavior of the other high mass particles (m > 1.2 GeV) whose ⟨pT⟩ measurement in p+p approaches the Au+Au value. This behavior suggests a possible smaller radial flow for heavy particles with respect to π and/or a more violent production mechanism for heavy particles in p+p collisions.

There is no significant suppression observed in the Σ(1385)/Λ ratios from p+p to 0 - 5% central Au+Au collisions. Since the previously measured suppression of K*(892)/K and Λ*(1520)/Λ ratios agrees with a signal loss via rescattering in the medium, the absence of suppression in the Σ(1385) ratio suggests a significant regeneration mechanism to recover the signal lost via rescattering [25, 26].

Acceptance and efficiency studies show that we should be able to find Θ+ pentaquarks at the few % level with the current data-set in d+Au and Au+Au collisions. Optimization of cuts to improve the signal over background is in progress. There is a possibility of measuring anti-pentaquarks at RHIC since the antibaryon to baryon ratio is approaching to one [27]. An upper limit to the yields and production mechanisms of pentaquarks in Au+Au collisions will be established in the 2004 run, which has a 70-fold increase in statistics over the current data.

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