K*$(892)^0$ Production in Relativistic Heavy Ion Collisions at $\sqrt{s_{NN}} = 130$ GeV

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Abstract. Preliminary results on the K*$(892)^0 \rightarrow \pi K$ production using the mixed-event technique are presented. The measurements are performed at mid-rapidity by the STAR detector in $\sqrt{s_{NN}} = 130$ GeV Au-Au collisions at RHIC. The K*0 to negative hadron, kaon and φ ratios are obtained and compared to the measurements in e$^+$e$^-$, pp and ¯pp at various energies.
1. Introduction

The main motivation for studying heavy-ion collisions at high energy is to investigate the properties of the strongly interacting matter at high densities and temperatures. In particular, the masses and widths of hadrons are expected to change in hadronic or nuclear matter compared to their vacuum values. Various theoretical models predict modification of hadron masses and widths in a dense and hot medium [2, 3]. In this context, the measurement of the properties of mesons whose lifetimes are of the order of the lifetime of the dense matter may be sensitive to the properties of the strongly interacting matter in which they are produced. For example, model calculations show that the $K^*0/K$ ratio is sensitive to the mass modification of particles in-medium and the dynamic evolution of the source [4].

Due to the re-scattering of the daughter particles, the resonances that decay into strongly interacting hadrons before thermal freeze-out may not be reconstructed. However, resonances with higher transverse momentum ($p_T$) may decay outside the system. As a consequence, the measurement of the yields and the $p_T$ distributions of resonances can provide information on the time between chemical and kinetic freeze-out of the system. In addition, we may be able to distinguish between a sudden freeze-out [5, 6] or a smooth hadronic expansion [7, 8] from a detailed comparison between the yield and the $p_T$ distribution of resonances and stable hadrons.

On the other hand, due to the large population of $\pi$’s and K’s [9, 10, 11] after chemical freeze-out, when the inelastic interactions are too infrequent to change the particle species and the total number of particles, the elastic interactions $\pi K \rightarrow K^*0 \rightarrow \pi K$ increase the $K^*0$ population compensating for the $K^*0$ resonances that decay before thermal freeze-out and may not be reconstructed.

Even though the hadronic decay modes for vector mesons are dominant, only the leptonic decay modes have been studied extensively mainly due to the large background from other produced hadrons and the broad mass width. However, Monte Carlo calculations have shown that the mixed-event technique [12, 13] should allow a statistical measurement of both $K^*(892)0$ and $\bar{K}^*(892)0$ at the Relativistic Heavy Ion Collider (RHIC) energies because the significance of the signal increases with the square root of the number of events.

Preliminary results from the first measurement of such short-lived resonance ($c\tau = 4 \text{ fm}$) via its hadronic decay channel in Au-Au relativistic heavy-ion collisions at $\sqrt{s_{NN}}= 130 \text{ GeV}$ using the STAR (Solenoidal Tracker At RHIC) detector at RHIC are presented. The ratios $K^*/h^-$, $K^*0/K$ and $\phi/K^*0$ are obtained and compared to the measurements in $e^+e^-$, pp and $\bar{p}p$ at various energies.

2. Data Analysis

The main STAR detector consists of a large Time Projection Chamber (TPC) [14] placed inside a uniform solenoidal magnetic field that provides the measurement of charged
particles. A scintillating Central Trigger Barrel (CTB) that surrounds the TPC is used as part of the centrality trigger by measuring the charged particle multiplicity. Two hadronic calorimeters (ZDCs) located upstream along the beam axis intercept spectator neutrons from the collision and provide the minimum bias trigger. The anti-correlation between the CTB and the ZDCs is used to trigger on the event centrality.

In the summer of 2000, the first collisions between Au nuclei at \( \sqrt{s_{NN}} = 130 \text{ GeV} \) took place at RHIC. During this period, the solenoidal magnet operated with a magnetic field of 0.25 T. About 440K central and 230K minimum bias events that survive the cuts mentioned below are used in this analysis. Central events correspond to 14% of the hadronic cross-section. For this analysis, only events with a vertex located within \( \pm 95 \text{ cm} \) of the center of the TPC along the beam direction are selected, and this assures uniform acceptance. The identification of the daughter particles from the \( K^*\) decay is obtained by the energy loss (dE/dx) in the gas of the TPC. The tracks are required to cross the entire active area of the detector, to satisfy a minimum number of points on the track cut, to point to the event vertex within a certain accuracy and to have a transverse momentum between 0.2 GeV/c and 2.0 GeV/c.

The decay channels \( K^* \rightarrow \pi^- K^+ \) and \( \bar{K}^* \rightarrow \pi^+ K^- \), each with a branching ratio of 2/3, are selected for the measurements. Due to limited statistics, the term \( K^*\) in this analysis refers to the average of \( K^*0 \) and \( \bar{K}^*0 \) unless specified. The invariant mass of every opposite sign \( K\pi \) pair is calculated for each event. The resulting invariant mass distribution consists of the resonance signal and the combinatorial background. The shape of the uncorrelated combinatorial background is determined using the mixed-event technique [12, 13]. Events are mixed for this background calculation if their centrality triggers are similar and their primary vertex locations are within 20 cm in the beam direction, which minimizes possible fluctuations and distortions in the uncorrelated background.

3. Results

The invariant mass distributions from same-event \( K\pi \) pairs and from mixed-event pairs are shown in the upper panel of Fig 1 for the 14% most central events. There are more than \( 14 \times 10^9 \) pairs of selected kaons and pions from these central events. The signal to background ratio is about 1/1000 for central and 1/200 for minimum bias events, which is significantly lower than 1/4 for pp at \( \sqrt{s_{NN}} = 63 \text{ GeV} \) [15]. The lower panel of Fig 1 depicts the \( K\pi \) invariant mass distribution after mixed-event background subtraction for the 14% most central hadronic interactions, where a 15 standard deviation (\( \sigma \)) of the \( K^*\) signal above the background fluctuation is observed.

The mixed-event technique [12, 13] describes the shape of the uncorrelated background distribution; therefore, only the signal and the correlated background are present in the distribution after background subtraction. In the case of the \( K\pi \) system, besides the \( K^*(892)^0 \) resonance, there is the \( K\pi \) and S-wave correlation [14], which is not a resonance, and a long list of higher resonant states. All these contribute
to the $K\pi$ correlation. In addition, particle misidentification of the decay products of $\rho$, $\omega$, $\eta$, $\eta'$ and $K^0_S$ produce correlations in the same-event distribution that are not present in the mixed-event distribution used to estimate the background. Studies using the HIJING model and an invariant mass distribution produced from like-sign $K\pi$ pairs from the data are consistent with the conclusion that the general features of the residual combinatorial background in the $K\pi$ invariant mass distribution after mixed-event background subtraction come from the correlations mentioned. Since a quantitative description requires the accurate knowledge of particle production and phase space distributions that are not yet measured at RHIC energies, the residual background was fit by both a linear and an exponential function. Separately, the differences between the results obtained from the two functions was about 20%. These differences are included in estimating the systematical uncertainties.

In order to obtain the $m_T - m_0$ spectra, the $K^{*0}$ signal is fit to a Breit-Wigner resonant function and corrected for detector acceptance and efficiency. The acceptance and reconstruction efficiency is determined by embedding simulated tracks into real
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Figure 2. $\left( K^*0 + \overline{K}^*0 \right)/2 m_T$ spectrum at mid-rapidity ($|y| < 0.5$) for the 14% most central interactions in the $p_T$ range from 0.4 GeV/c to 3.2 GeV/c. The errors shown are statistical only.

 events at the raw data level, reconstructing the full events and comparing the simulated input to the reconstructed output. The acceptance and efficiency factor, $\epsilon$, depends on the event centrality, the transverse momentum and the rapidity of the parent and daughter particles. $\epsilon$ varies from under 15% for $p_T \simeq 0$ GeV/c to about 35% for $p_T \simeq 2.0$ GeV/c.

The $d^2N/(2\pi m_T dm_T dy)$ distribution as a function of $m_T - m_0$ for central interactions at mid-rapidity ($|y| < 0.5$) is shown in Fig. 2. An exponential fit is used to extract the $K^*$ yield per unit of rapidity around mid-rapidity and the inverse slope ($T$). We obtain $dN/dy = 10.0 \pm 0.8$ (stat) and $T = 0.41 \pm 0.02$ (stat) GeV. The $K^*$ and $\overline{K}^*$ invariant mass distributions integrated in $p_T$ are fit separately to a Breit-Wigner resonant function and a linear residual background. The ratio $K^*/K^* = 0.92 \pm 0.14$ (stat) is obtained for central collisions. Therefore, the average value between $K^*$ and $\overline{K}^*$ should well represent the $K^*(892)^0$ production within our statistics. The systematical uncertainty in $dN/dy$ is estimated to be 25% due to both detector effects and the uncertainty in the background determination. By varying the analysis cuts and studying the detector effects, the systematical uncertainty in the inverse slope is estimated to be 10%. Due to limited statistics in the minimum bias data set, we assume that the $K^*0$ $m_T$ distribution for both central and minimum bias events have the same shape, and in this way we can estimate the $K^*0$ yield. The result is $dN/dy = 4.5 \pm 0.7$ (stat) $\pm 1.4$ (sys). The difference between [17] and the results presented here is that we are able to measure the slope of $410 \pm 20$ (stat) MeV instead of an assumed 300 MeV slope, and we use a linear function to describe the background instead of an exponential
function. Each of these lowers the yield by about 20%.

The $K^*/h^-$ ratios measured for central and minimum bias events are compared to the measurements in pp [17] and $e^+e^-$ [18, 19, 20]. The $h^-$ yield corresponds to the corrected primary negatively charged hadrons at $|\eta| < 0.5$ [21]. At $\sqrt{s_{NN}} = 130$ GeV, $K^*/h^- = 0.042 \pm 0.004$ (stat) $\pm 0.01$ (sys) for central collisions and $K^*/h^- = 0.059 \pm 0.008$ (stat) $\pm 0.019$ (sys) for minimum bias events. These results are compared to $K^*/\pi = 0.057 \pm 0.012$ measured in pp at $\sqrt{s_{NN}} = 63$ GeV [15] and $K^*/\pi = 0.044 \pm 0.003$ measured in $e^+e^-$ at $\sqrt{s_{NN}} = 91$ GeV [15, 18, 20]. The error in the measurements in pp and $e^+e^-$ corresponds to the quadratic sum of the systematical and statistical errors. Noting that about 80% of $h^-$ are pions at RHIC energies, we observe that the $K^*/h^-$ ratio is comparable to the $K^*/\pi$ ratios measured in pp and $e^+e^-$. We do not observe the enhancement in the $K^*$ production observed for other strange particles as function of increasing energies and colliding systems [1].

Fig 3 shows the $K^*/K$ and $\phi/K^*$ ratios measured in different colliding systems at various energies. The $K^*/K$ ratio is interesting because $K^*$ and K have similar quark content and differ mainly in mass and spin. Fig 3 shows that the ratio $K^*/K = 0.26 \pm 0.03$ (stat) $\pm 0.07$ (sys) measured in central Au-Au collisions at 130 GeV beam energy is compatible or even lower than the measurements in pp, pp and $e^+e^-$ at lower energies.

The $\phi/K^*$ ratio measures the strangeness suppression in near ideal conditions since $\Delta S = 1$ with hidden strangeness in the $\phi$, and there is only a small mass difference. Fig 3 shows an increase of the ratio $\phi/K^* = 0.49 \pm 0.05$ (stat) $\pm 0.12$ (sys) measured in central Au-Au collisions at 130 GeV beam energy [27] compared to the measurements

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**Figure 3.** $K^*/K$ and $\phi/K^*$ ratios measured in different colliding systems at various energies. The ratios are from measurements in $e^+e^-$ collisions at 10.45 GeV [22], 29 GeV [23], 90 GeV [18] and 91 GeV [19, 20] beam energies, $\bar{p}p$ at 5.6 GeV [24] and pp at 27.5 GeV [25], 52.5 GeV [26] and 63 GeV [15]. The errors shown correspond to the quadratic sum of the statistical and systematical errors.
in pp and $e^+e^-$ at lower energies. However, this increase may not be solely related to strangeness suppression due to additional effects on short lived resonances in heavy-ion collisions. It is also interesting to note that the $\phi/K^*0$ ratio already has a rising tendency as a function of beam energy in pp and $e^+e^-$. Since the $K^*$ lifetime is short ($c\tau = 4$ fm) and comparable to the time scale of the evolution of the system in relativistic heavy-ion collisions, the $K^*$ survival probability needs to be taken into account. This survival probability depends on the expansion time between chemical and thermal freeze-out, the source size and the $K^*$ transverse momentum. Should the $K^*$ decay between chemical and thermal freeze-out, the daughters from the decay may re-scatter and the $K^*$ will not be reconstructed. On the other hand, chemical freeze-out is only truly defined for non-resonant long-lived particles. Elastic interactions such as $\pi K \rightarrow K^*0 \rightarrow \pi K$ are still effective and regenerate the $K^*$ until thermal freeze-out. Due to these additional effects on short lived resonances in heavy-ion collisions, the $K^*$ measurement at RHIC may provide information on the expansion time between chemical and thermal freeze-out. However, final state interactions of the hadronic decay products destroy the early-time information carried by these decays. Assuming that the difference in the $K^*/K$ ratio measured in Au-Au collisions at RHIC and the ratios measured in pp and $e^+e^-$ is due to the $K^*$ survival probability, our measurement is consistent with an expansion time of only a few fm between chemical and thermal freeze-out (sudden freeze-out). In the scenario of a long expansion time between chemical and thermal freeze-out (~20 fm) and without $K^*$ regeneration, not only is the measured $K^*$ production reduced but there is also a low $p_T$ depression. This results in a large effective inverse slope than would otherwise be expected. However, the measured $K^*$ inverse slope is similar to the $\phi$ inverse slope and higher than that of kaons. Hence, our measurement at RHIC is consistent with either a sudden freeze-out with no $K^*$ regeneration or a long expansion time scenario with significant $K^*$ regeneration. In the statistical model, the measured $K^*$ should be consistent with the condition at kinetic freeze-out instead of chemical freeze-out. The fact that the statistical model reproduces our measurement is consistent with a short expansion time between chemical and thermal freeze-out, since the statistical model provides particle yields at chemical freeze-out.

4. Conclusions

Preliminary results on $K^*(892)^0$ and $\overline{K}^*(892)^0$ production measured at mid-rapidity by the STAR detector in $\sqrt{s_{NN}} = 130$ GeV Au-Au collisions at RHIC were presented. Despite the short lifetime ($c\tau = 4$ fm), the data show significant $K^*$ production. However, we do not observe an enhancement in the $K^*$ production as observed for other strange particles for increasing energies and differing colliding systems. If the difference in the $K^*/K$ ratio measured in Au-Au collisions at RHIC and the ratios measured in pp and $e^+e^-$ is due to the $K^*$ survival probability, our measurement is consistent with a sudden freeze-out. Hence, the $K^*$ production at RHIC rules out a long expansion
time between chemical and thermal freeze-out unless there is \( K^{*0} \) regeneration, due to elastic interactions after chemical freeze-out.

Finally, the study of resonances like the \( K^{*0} \) may provide important information on the collision dynamics. The improvement of the uncertainties in the \( K^{*0} \) and \( \phi \) measurements and the measurements of other resonances with different properties may help in understanding the development of the system after chemical freeze-out.

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