Probing hadronic rescattering via resonance production in Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV from STAR BES-II

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Abstract

Short-lived resonances, like K^{*0}, are useful tools to study particle production mechanisms and the properties of the hadronic phase at the late stage of heavy-ion collisions. Properties of the resonances are expected to be modified due to the interaction of their decay daughters with the hadronic medium via the rescattering and regeneration processes. The particle yield ratios ($K^{*0}/K, \phi/K^{*0}$) can provide information about the interplay between these in-medium effects. Recently, the STAR experiment at RHIC has accumulated high-statistics data samples of Au+Au collisions with enhanced detector capabilities and a wider pseudorapidity coverage during the Beam Energy Scan phase-II (BES-II) program, which also help extend resonance measurements.

We will report on the measurement of the production of K^{*0} resonances in Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV. Results include transverse momentum (p_T) spectra, mean transverse momenta and the integrated yield as a function of rapidity and charged particle multiplicity. The resonance to non-resonance ratios (K^{*0}/K) will be shown as a function of centrality to study the rescattering/regeneration effects. An estimate of the lower limit of the hadronic phase lifetime will be shown as a function of centrality.

Keywords:
RHIC, Resonances, Hadronic rescattering, Beam Energy Scan

1. Inroduction

Relativistic heavy-ion collisions provide a unique setting to investigate QCD matter under varied temperatures and densities [1, 2]. Resonances have extremely short lifetimes, which is in the order of 10^{-23} seconds. As they decay so quickly, they are excellent candidate to probe the late-stage hadronic phase created in high energy heavy-ion collisions [3, 4]. Light-flavor resonance particles like K^{*0} meson that has a lifetime of about 4.16 fm/c, which is much shorter than the lifetime of the fireball ($\sim$ 10 fm/c) created in these collisions. Hence these resonances decay within the hadronic phase thereby making the decay daughters prone to various in medium hadronic interactions. Between chemical freeze-out (when inelastic interactions stop) and kinetic freeze-out (when elastic interactions cease), these decay products can undergo rescattering and regeneration, which may alter the observed yield of the parent resonances.

When the K^{*0} meson decays before kinetic freeze-out, its decay products (π and K) may undergo re-scattering with other hadrons in the medium, altering their momenta and preventing the successful reconstruction of the parent resonance. This leads to a reduction in the observed K^{*0} yield. Conversely, pions and kaons in the medium can interact via pseudo-elastic scattering to regenerate K^{*0} mesons, thereby increasing the yield. The final observed yield is thus determined by the interplay between re-scattering and regeneration, which can be studied using the resonance-to-nonresonance ratio, such as K^{*0}/K [4, 5].

Hence study of the resonances across different collision system and collision energies will be helpful to systematically understand the hadronic phase in heavy-ion collisions [3, 4, 5, 6].

2. Data Sets and Analysis details

These proceedings report on precise measurements of K^{*0} meson production in Au+Au collisions at $\sqrt{s_{NN}}$ =19.6 GeV, based on high-statistics data from the BES-II program. Particle identification was carried out using both the Time Projection Chamber (TPC) and the Time of Flight (TOF) detectors. As part of the BES-II upgrades, the inner TPC (iTPC) was upgraded, resulting in better track momentum resolution, lower transverse momentum reach and extended pseudorapidity coverage ($|\eta| < 1.5$, previously $|\eta| < 1.0$). For quality event selection, the primary vertex position is required to lie within $|V_z| < 145$ cm along the beam direction and $|V_r| < 2$ cm in the radial direction.

In the BES measurements, reported here, K^{*0} and $\overline{K^{*0}}$ are combined and collectively referred to as K^{*0} throughout the text. Similarly, charged kaons

($K^{\pm}$) are combined and denoted as K. The $K^{*0}(\overline{K^{*0}})$ is reconstructed via its hadronic decay channel K^{*0} $(\overline{K^{*0}}) \rightarrow K^{+}\pi^{-}$ $(K^{-}\pi^{+})$(Branching ratio 66.6%). To estimate the combinatorial background, the track rotation method is used. In this method, the momentum of one of the daughter tracks (in this case, the pion) is rotated by 180° in the transverse plane to destroy any real correlation between the decay products that originated from the same parent particle. The resulting background is then subtracted from the distribution of same-event $K\pi$ pairs to extract the true K^{*0} signal. The extracted signal is fitted with a Breit-Wigner function, along with a polynomial function to account for remaining residual background. The final yield of the K^{*0} mesons is obtained by integrating the signal peak after subtracting this residual background.

3. Results

3.1. Transverse momentum (p_T) spectra

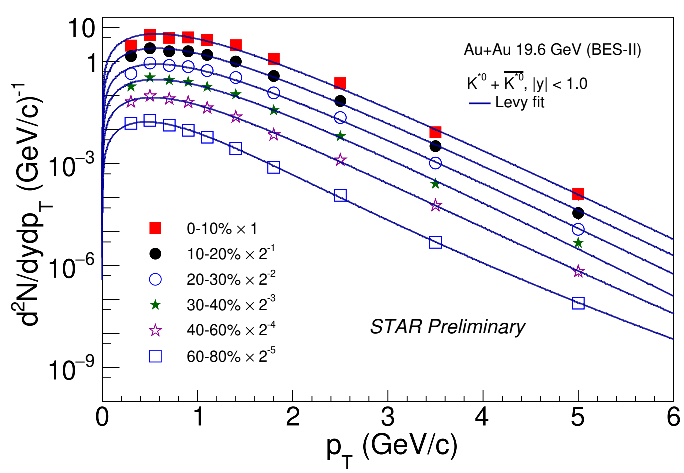

Figure 1: K^{*0} meson transverse momentum (p_T) spectra at mid rapidity ($|y| < 1.0$) for Au+Au collisions at 19.6 GeV. The uncertainties are within the marker size.

Figure 1 shows the mid rapidity ($|y| < 1.0$) transverse momentum (p_T) spectra of K^{*0} meson for Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV. The spectra are fitted with Levy-Tsallis function to extrapolate the yields into the unmeasured regions.

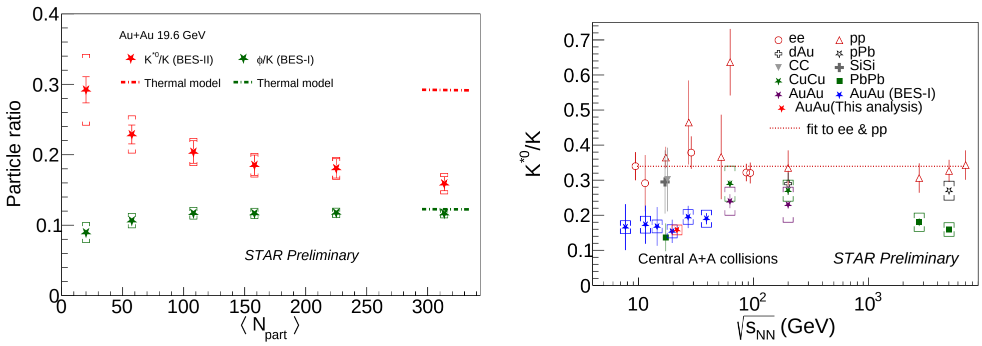

Figure 2: Left panel: Resonance-to-non-resonance ratios as a function of $\langle N_{part} \rangle$, shown alongside thermal model predictions presented as dotted lines [5]. The ratios K^{*0}/K and ϕ/K (from BES-I) represent $(K^{*0} + \overline{K^{*0}})/(K^{+} + K^{-})$ and $2\phi/(K^{+} + K^{-})$, respectively [2, 7]. The K^{*0} results are based on BES-II data, while kaon yields are taken from BES-I measurements [2]. Right panel: The energy and system size dependence of the K^{*0}/K ratio [4]. Statistical and systematic uncertainties are represented by bars and caps, respectively.

3.2. Particle ratios

The left panel of Fig. 2 shows the resonance to non-resonance ratio (K^{*0}/K and ϕ/K) as a function of the average number of participating nucleons, $\langle N_{part} \rangle$. A decrease in the K^{*0}/K ratio from peripheral to central collisions is observed, indicating a significant loss in K^{*0} yield due to hadronic rescattering. In contrast, the ϕ meson, with a much longer lifetime ($\sim$46 fm/c) about 10$\times$ that of the K^{*0} meson, is assumed to be less affected by such in-medium interactions, resulting in a centrality-independent ϕ/K ratio. Furthermore, thermal model predictions that do not incorporate hadronic phase effects overestimate the K^{*0}/K ratio in central collisions but show good agreement with the ϕ/K measurements. The right panel of Fig. 2 presents the K^{*0}/K ratio as a function of collision energy for both elementary and heavy-ion systems. The ratio is suppressed in central A+A collisions compared to elementary or small systems, where no/infinitesimally short-lived hadronic phase is expected. Together, these observations indicate a dominant hadronic rescattering over regeneration in central heavy-ion collisions.

3.3. Estimate of lower limit of hadronic phase lifetime

The time interval between chemical freeze-out and kinetic freeze-out is loosely regarded as the lifetime of the hadronic phase. Since this duration cannot be measured directly from experiments, an alternative toy-model approach is employed to estimate it [4]. The model is inspired from nuclear decay law and formulated as follows;

$$\left(\frac{K^{*0}}{K}\right)_{Kin.freezeout} = \left(\frac{K^{*0}}{K}\right)_{Chem.freezeout} \times e^{-\Delta t/\tau_{K^{*0}}}, \tag{1}$$

This relation is based on the assumptions that the $(K^{*0}/K)_{Chem.freezeout}$ and $(K^{*0}/K)_{Kin.freezeout}$ ratios correspond to those measured in elementary and heavy-ion collisions, respectively. Since there is no direct measurement of the (K^{*0}/K) ratio in $p+p$ collisions at $\sqrt{s_{NN}}$ =19.6 GeV, we use a value of 0.34 ± 0.01, obtained from a fit to existing e+e and p+p data. It is further assumed that no regeneration of K^{*0} occurs between chemical and kinetic freeze-out, and that all K^{*0} mesons decay before kinetic freeze-out. Here, Δt represents the hadronic phase lifetime, and $\tau_{K^{*0}}$ is the vacuum lifetime of the K^{*0} meson. The extracted Δt is then boosted by a Lorentz factor, given by $\sqrt{1 + (\langle p_T \rangle_{K^{*0}}/mc)^2}$.

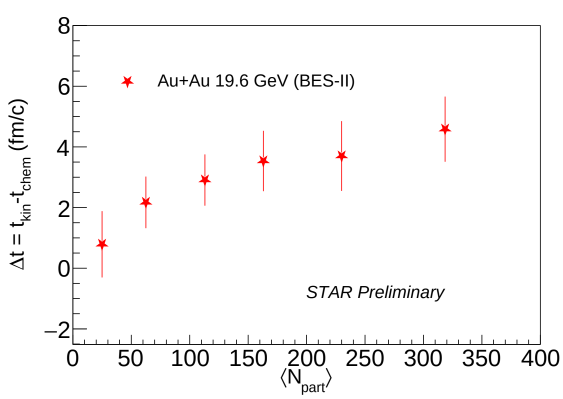

Figure 3: The lower limit of hadronic phase lifetime (Δt) as a function of $\langle N_{part} \rangle$. The error bars are the quadratic sum of statistical and systematic uncertainties.

Figure 3 shows the lower limit of the hadronic phase lifetime as a function of N_{part} in Au+Au collisions at $\sqrt{s_{NN}}$ = 19.6 GeV. The lifetime appears to increase from peripheral to central collisions. This trend is consistent with the expectation that the kinetic freeze-out temperature decreases from peripheral to central collisions, assuming a constant chemical freeze-out temperature, as reported by earlier measurements [2].

4. Summary

The new measurements of K^{*0} meson production in Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV are reported using high-statistics BES-II data. The resonance to non-resonance ratio (K^{*0}/K) shows a decreasing trend from peripheral to central collisions, indicating dominant hadronic rescattering effects in central heavy-ion collisons. In contrast, the ϕ/K ratio remains flat due to the longer lifetime of the ϕ meson. Thermal model predictions overestimate the K^{*0}/K in central collisions, further supporting the rescattering phenomenon. The estimated lower limit of the hadronic phase lifetime, from toy model increases from peripheral to central collisions, agreeing with the expectations from decreasing kinetic freeze-out temperatures.

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