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STRANGE QUARK DYNAMICS AT RHIC*

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Hot dense matter were created at RHIC. Strange quark dynamics are both useful and important in identifying and understanding the properties of the state with partonic degree of freedom. In Au+Au collisions at 200 GeV, the value of strangeness phase space factor γ_s approaches 1 in the most central collisions. Nuclear modification factor ($R_{\rm CP}$) and elliptic flow (v_2) of strange baryons ($\Lambda + \overline{\Lambda}$, $\Xi^- + \overline{\Xi}^+$, $\Omega^- + \overline{\Omega}^+$) in the intermediate $p_{\rm T}$ region of 2–5 GeV$/c$ are consistent among them and with those of protons, indicating similar quark dynamics in baryon formation between s quarks and light u, d quarks. It is consistent with a scenario of quark recombination/coalescence mechanism based on constituent quark degree of freedom in baryon formation from a nearly strange equilibrated state with high strange quark density in central Au + Au collisions at RHIC.

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1. Introduction

By Lattice Quantum ChromoDynamics (LQCD) prediction, a new form of matter called Quark Gluon Plasma (QGP) could be created at zero-baryon density at temperature of about 160–170 MeV [1]. In the state of QGP, de-confined partons (quarks and gluons) exist. Therefore, identifying and studying the properties of such matter with partonic degree of freedom are among the major physics goals at RHIC. In nuclear collisions at RHIC, the formed system is highly dynamic. It is generally believed that a collective set of probes are needed to understand the evolution of such a system in both space and time dimensions.

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Hard scatterings of partons occur early in the evolution of the expanding system, thereby high p_{T} particles and correlation of back-to-back jets probe the phase of highest density. In central Au + Au collisions at RHIC, suppression of high p_{T} particles [2–4] and disappearance of back-to-back high p_{T} hadron correlation [5] have been observed. Partons transverse a dense medium lose energy through gluon bremsstrahlung [6, 7] and those observations are in qualitative agreement with predictions of large parton energy loss in dense medium. Further measurements from $d+\mathrm{Au}$ collisions showed that the inclusive yield of hadrons is enhanced in $d+\mathrm{Au}$ collisions relative to the binary-scaled pp collisions while the two-particle azimuthal distributions are very similar in both of them. Therefore the strong suppression of the inclusive yield and back-to-back correlations at high p_{T} are due to final-state interactions with the dense medium generated in such collisions [8].

Bulk properties of the system formed in nuclear collisions can be reflected by spectra of measured particles and their collective motion. The centrality and p_{T} dependences of various particle species provide rich information on both the temperature of the system at different stages and the mechanism of hadron formation. Recent results from RHIC show the chemical freeze-out temperature T_{ch} is about $160-170$ MeV [9], which is comparable to the critical temperature for the QGP formation. Measurements of scaling properties of proton and pion [10], K_S^0 and Λ [11] have also shown distinctive collision dependence between baryons and mesons at intermediate p_{T} with baryons experiencing less suppression than mesons. The measured saturation values of elliptic flow (v_2) for K_S^0 and Λ also showed distinctive difference in the intermediate p_{T} region [12]. Models based on the formation of hadrons from co-moving quarks (quark coalescence or recombination) [13–15] have been proposed to explain these observations. These models assume a constituent quark degree of freedom and are very different from parton fragmentation for hadron formation. Thus, study on the particle spectra and their collective motion could be another unique signature for the QGP formation at RHIC.

The high density and large energy loss of partons occurred in the Au + Au collisions at RHIC are ideal for particles to develop collective motions and thermalization. In this section, we will focus on strange quark dynamics such as strange phase-space factor γ_s, nuclear modification factor R_{CP} and elliptic flow of strange baryons.

2. Results of strange phase-space factor γ_s

Strangeness phase-space occupancy factor γ_s has been used to describe the suppression of strange quarks relative to light up and down quarks in a bulk matter. It measures to which extent s quarks have reached the equilibration. The centrality dependence of the γ_s factor provides a quantitative

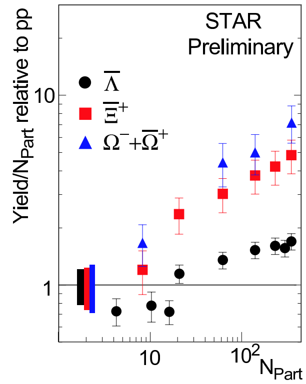

Fig. 1. Strangeness enhancement effects at RHIC at 200 GeV.

measure of strangeness evolution in bulk matter as a function of collision centrality. Figure 1 shows the anti-strange particle yield per participant in 200 GeV dAu and AuAu collisions, normalized by the yield in pp collisions at the same energy. From pp to central AuAu collisions, there are clear enhancement effects in the yield per participant and that enhancement effect is greater for multi-strange anti-baryons ($\overline{\Xi}^+$,$\overline{\Omega}^+$) than for strange baryon ($\overline{\Lambda}$). The dependence of the enhancement on both the system volume (number of participants) and strangeness content of particles suggests an increasing strange quark density in the system from peripheral/elementary collisions to central AA collisions. That increase in turn could result in an increased strange phase-space occupancy. In figure 2 are the results of γ_s as func-

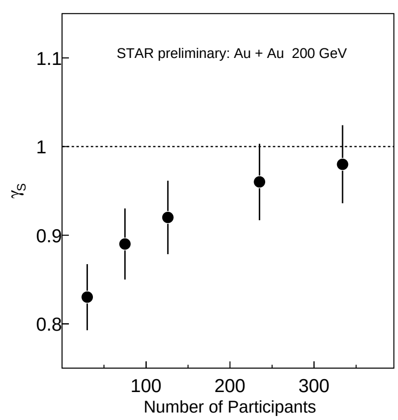

Fig. 2. γ_s as a function of number of participants. γ_s was calculated from thermal model fits to the measured particle yields ($\pi, k, p, \Lambda, \Xi, \Omega$ and their anti-particles) at 200 GeV.

tion of centrality in AuAu collisions at 200 GeV. The γ_s is about 0.8 in the most peripheral centrality and that value increase to almost 1 in the most central collisions. The $\gamma_s = 1$ indicates that strange quarks are approaching an equilibrated state in the hot dense matter created in central Au + Au collisions.

3. Results of nuclear modification factor for strange baryons

High $p_{\rm T}$ particles are produced from initial hard parton scatterings whose cross-sections are assumed to be proportional to the number of binary nucleon–nucleon collisions $N_{\rm bin}$. The $N_{\rm bin}$ scaled centrality ratio $R_{\rm CP}$ is a measure of the particle production's dependence on the collision system's size and density:

$$R_{\rm CP}(p_{\rm T}) = \frac{d^2N_{\rm central}/(N^{\rm central}_{\rm binary}\, dp_{\rm T}dy)}{d^2N_{\rm peripheral}/(N^{\rm peripheral}_{\rm binary}\, dp_{\rm T}dy)}\,, \tag{1}$$

where $R_{\rm CP} = 1$ if particle production is equivalent to a superposition of independent nucleon–nucleon collisions.

Figure 3 shows the $R_{\rm CP}$ measurements for $\Lambda+\overline{\Lambda}$, $\Xi^-+\overline{\Xi}^+$ and $\Omega^-+\overline{\Omega}^+$ at mid-rapidity in Au + Au collisions at RHIC at 200 GeV. In this figure, we note (1) at intermediate $p_{\rm T}$, the $p_{\rm T}$ dependencies of $R_{\rm CP}$ for $\Lambda+\overline{\Lambda}$, $\Xi^-+\overline{\Xi}^+$ and $\Omega^-+\overline{\Omega}^+$ are similar independent of their masses; (2) At intermediate $p_{\rm T}$ from 1.8 GeV/c to 3.5 GeV/c, the $R_{\rm CP}$ of hyperons exhibits little suppression while mesons (approximated by the dashed line) have distinctively different

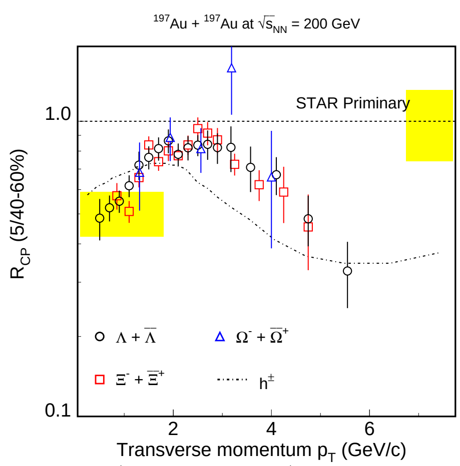

Fig. 3. $R_{\rm CP}$ for $\Lambda+\overline{\Lambda}$, $\Xi^-+\overline{\Xi}^+$ and $\Omega^-+\overline{\Omega}^+$ at mid-rapidity (centrality interval 0–5% *versus* 40–60%). Dashed line for charged hadrons are shown as comparison.

trend. The differences between strange baryon $R_{\rm CP}$ and strange meson $R_{\rm CP}$ in the intermediate $p_{\rm T}$ region indicate possible different dynamics and hadronization mechanism in strange baryon and strange meson production in that $p_{\rm T}$ region [12]. However, the similar $R_{\rm CP}$ of baryons at intermediate $p_{\rm T}$ indicate similar centrality dependence between s quarks and $u(d)$ quarks and suggest the same dynamics of s quarks as $u(d)$ quarks in the intermediate $p_{\rm T}$ region.

4. Results of elliptic flow (v_2) for strange baryons

In high energy nuclear collisions, the elliptic flow of particles is due to the fact that the density is highest in the center of the created fireball and vanishes at the boundary. The collective flow caused by such matter density gradient measures the strength of the interactions between constituents. Since the collective flow is additive, it can carry information from stages as early as the partonic phase. At low $p_{\rm T}$ (< 2 GeV/c), the elliptic flow v_2 is well described by hydrodynamic calculations [11]. However, hydrodynamic calculations over-predict at higher $p_{\rm T}$. The results are shown in figure 4(a). The dot-dashed lines are fits on K_S^0 and $\Lambda + \overline{\Lambda}$ data points. Figure 4(b) and (c) are the v_2 for multi-strange baryons $\Xi^- + \overline{\Xi}^+$ and $\Omega^- + \overline{\Omega}^+$. Within statistical uncertainties, multi-strange baryon v_2 are consistent with that of Λs. Multi-strange baryon have smaller hadronic cross-sections [16], therefore, their none-zero values of v_2 suggest they might be mostly related to early partonic interactions. Moreover, the interesting v_2 dependence on the number of constituent quarks (figure 4(d)) has been explained by the coalescence approaches [13, 15]. In the coalescence model, hadrons at intermediate $p_{\rm T}$ formed by co-moving quarks and v_2/n *versus* $p_{\rm T}/n$ reveals the momentum-space azimuthal anisotropy of partons in a bulk matter. With this scenario, the difference between meson and baryon is a natural result and it is also easy to understand the $R_{\rm CP}$ difference between mesons and baryons with baryon $R_{\rm CP}$ greater than meson $R_{\rm CP}$ in the intermediate $p_{\rm T}$ region. At higher $p_{\rm T}$ where independent fragmentation is likely to dominant over multi-parton coalescence in hadron production, the constituent-quark-scaling is expected to break down and the v_2 and $R_{\rm CP}$ should take on a value closer to that of an underlying partonic v_2 or partonic $R_{\rm CP}$. This was supported by the converge of $R_{\rm CP}$ for baryons and mesons at $p_{\rm T}$ of 5 GeV/c in figure 3.

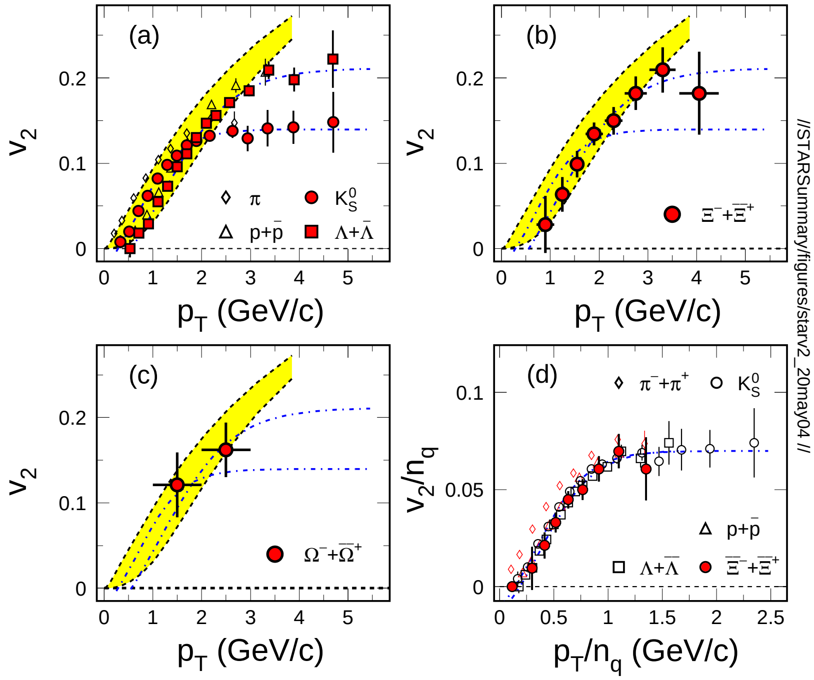

Fig. 4. Transverse momentum dependence of the event anisotropy parameters. (a) for π,K^0_S, p and $\Lambda + \overline{\Lambda}$. (b) for $\Xi^- + \overline{\Xi}^+$. (c) for $\Omega^- + \overline{\Omega}^+$. (d) v_2 scaled by number of constituent quarks (n) and plotted *versus* p_{T}/n. Dot-dashed lines are the results from fits of data. Hydrodynamic calculations are shown as thick-dashed-lines.

5. Conclusions

Dense matter has been created at RHIC. The increasing γ_s as function of centrality in Au + Au collisions indicates s quarks approach equilibrium. The strange baryon R_{CP} and v_2 measurements in the intermediate p_{T} region are consistent with the quark coalescence model. If proved, this could be a key signature of QGP.

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