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Transverse expansion in $^{197}\text{Au} + ^{197}\text{Au}$ collisions at RHIC

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Abstract Using the RQMD model, transverse momentum distributions and particle ratios are studied for $^{197}\text{Au} + ^{197}\text{Au}$ collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV. In particular, we present results on the mean transverse momentum of charged pions, charged kaons, protons and anti-protons and compare with experimental measurements. We discuss an approach to study early partonic collectivity in high energy nuclear collisions.

Understanding the physics of relativistic heavy ion collisions represents an attractive problem, providing us the chance to create and investigate extremely hot and dense hadronic matter, the quark-gluon plasma [1]. Almost three years ago, the Relativistic Heavy Ion Collider (RHIC) started operation and a variety of new and exciting data has been reported [2, 3]. Experimental phenomena like strong collective expansion [4, 5, 6], large values of the elliptic anisotropy parameter $\langle v_2 \rangle$ [7], the suppression of charged particle yields at moderately high transverse momentum [8], and the disappearance of back to back correlations of particles at moderately high transverse momentum [9] were observed. These observations indicate that frequent interactions among partons (quarks and gluons) occur in high energy nuclear collisions. However, the question of whether those interactions take place among hot-equilibrated partons or among those partons originating from the incoming fast nuclei is yet to be answered. Complicated processes during the multi-particle production and interactions are difficult to describe in a theoretical frame-

work. Microscopic transport models are necessary for investigating high energy nuclear collisions.

In high energy nuclear collisions, the density distribution of particles and interactions among them lead to a pressure gradient which drives the collective expansion. Here, collectivity is cumulative over the whole collision process. The study of observables related to collective expansion, i.e. transverse radial flow will help us to understand the collision dynamics. Furthermore, interactions at the late stage tend to wash out the memory of the early stage information. However, the amount of collectivity finally observed by the detector does not depend on the nature of the constituents - partons or hadrons, as long as the collective flow is strong. Therefore we focus on the collective flow observables and use the RQMD model [10] as a guidance.

Within the framework of RQMD, a typical heavy ion collision may be schematically divided into three stages, *i.e.* pre-hadronic stage, hadronic pre-equilibrium stage and the stage from hadronic kinetic equilibrium to freeze-out. The pre-hadronic stage is determined by the initial excitation and fragmentation of color strings and ropes. This stage lasts about $1.5 fm/c$ and the effective transverse pressure is rather soft. During the late hadronic stage, the hadronic system reaches local kinetic equilibrium followed by a break-down of equilibrium due to dilution of the hadronic gas and finite size of the system [4, 11].

One of the characteristic features of transverse radial flow is the mass dependence of the mean transverse momentum $\langle p_T \rangle$, which is re-

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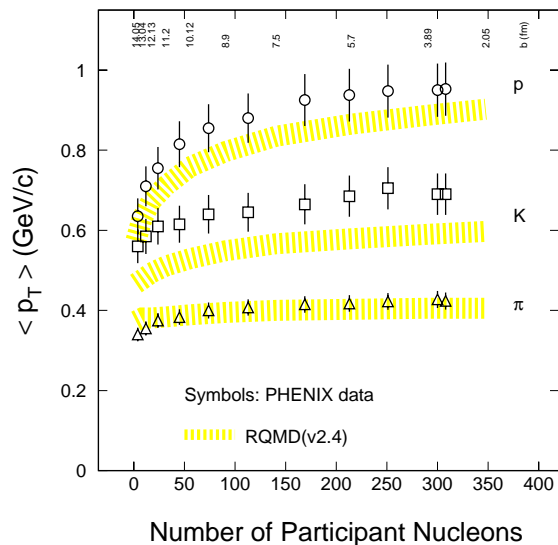


Figure 1: Mid-rapidity mean transverse momentum $\langle p_T \rangle$ of charged pions (triangles), charged kaons (squares), and (anti-)protons (circles) vs. collisions centrality (number of participants) for $^{197}\text{Au} + ^{197}\text{Au}$ collision at $\sqrt{s_{NN}} = 200$ GeV. The symbols show preliminary data from the PHENIX Collaboration [12] and the errors are statistical only. The dashed bands represent the results from RQMD [10]. Note that for all particles, the data points are extracted from $|y| \leq 0.35$ and the model calculation are from $|y| \leq 0.5$. The values of impact parameters from the model are also listed in the top part of the figure.

flected in the corresponding slope parameters [6]. Figure 1 shows the $\langle p_T \rangle$ for charged pions (π), charged kaons (K) and (anti-)protons (p) as a function of the collision centrality. Preliminary data from the PHENIX collaboration [12] are given by the symbols, results from RQMD are shown as hatched bands. With increasing centrality the values of $\langle p_T \rangle$ increase and the difference between particles also increases, indicating the development of stronger collective motion in more central collisions. The RQMD model reproduces this trend although it underestimates the absolute values for kaons throughout the whole centrality range.

Switching off re-scattering among produced particles in RQMD results in flat distributions of $\langle p_T \rangle$ as a function of centrality for pions and

kaons. The variation for (anti-)protons is less than 10%. All values correspond to the most peripheral collisions, *i.e.* $\langle p_T \rangle \approx 0.38, 0.47, 0.58$ GeV/c for charged pions, charged kaons, and (anti-)protons, respectively. These results demonstrate the importance of re-scattering in high energy nuclear collisions. The RQMD model does not include partonic degrees of freedom. However, at RHIC energies the re-scattering needed to describe the $\langle p_T \rangle$ and ratios of particles might occur at an earlier stage. The fact that RQMD underpredicts [13] the value of $\langle v_2 \rangle$ suggests that interactions among partons at the early stage of the collision are important at RHIC.

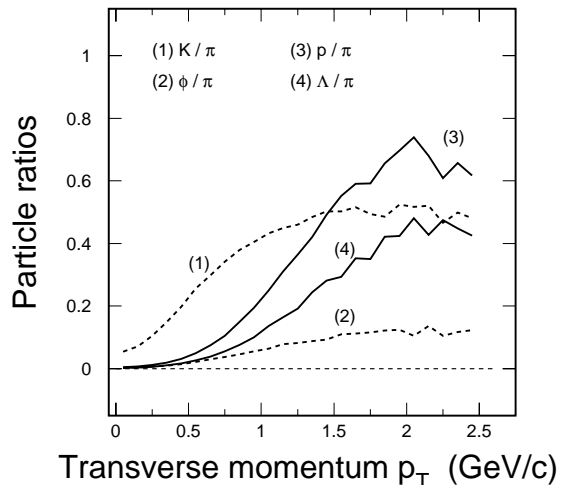


Figure 2: Transverse momentum dependence of the mid-rapidity particle ratios of charged kaons over charged pions (K/π), ϕ -mesons over charged pions (ϕ/π), (anti-)protons over charged pions (p/π), and (anti-)lambdas over charged pions (Λ/π), from $^{197}\text{Au} + ^{197}\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV by RQMD. The results are from the 10% most central ($b \leq 3$ fm) collisions. Recent results ref. [14] show that the sum of proton and lambda over pion ratio is approach unity at $p_T \sim 2.5$ GeV/c, similar to the RQMD results.

One of the new observations at RHIC is that at moderately high transverse momentum $p_T \sim$

2-3 GeV/c, the mid-rapidity yields of protons are approaching or are equal to that of negatively charged pions [5]. This observation has been interpreted as the result of either baryon-junction [15] or parton coalescence [16, 17]. In the former case, the novel mechanism of baryon transport, the existence of topological gluon field configurations in high energy collisions, is invoked [18, 19, 20]. The junction model predicts long range baryon number transport over rapidity and considerable transverse momentum p_T enhancement [20]. In the latter case, the observed strong enhancement in the proton to pion ratio is discussed in the framework of quark coalescence [16, 17]. As a consequence, collectivity at the partonic level becomes important.

In Fig. 2, several particle ratios from calculations with RQMD are shown as a function of p_T . The solid lines and dashed lines represent the baryon over pion and meson over pion ratios, respectively. All ratios increase as p_T increases, but the ratios from protons reach much higher values than those of ϕ -mesons. In this model, the enhancement is mainly due to multiple re-scattering among produced particles. In the limit of frequent re-scattering, the hydrodynamic behavior is expected to appear as discussed in Ref. [21].

In the calculations, the strong enhancement of protons over pions as a function of transverse momentum comes from the re-scattering at the late hadronic stage. On the other hand, as proposed in Ref. [16, 17], the collectivity may have developed at the early partonic stage in high energy collisions at RHIC. Pions and protons might dominantly participate in re-scattering at the late hadronic stage. Since collectivity is cumulative, one can not unambiguously identify the dominant origin of the collectivity from the measurement of pions and protons only. The study of other particle species with much smaller hadronic cross sections will allow us to identify and characterize collectivity at the partonic stage.

As shown in Fig. 2, the ratio of ϕ -mesons over charged pions (ϕ/π) is much lower than that of either (anti)-protons over charged pions (p/π) or (anti)-lambdas over charged pions (Λ/ϕ). This

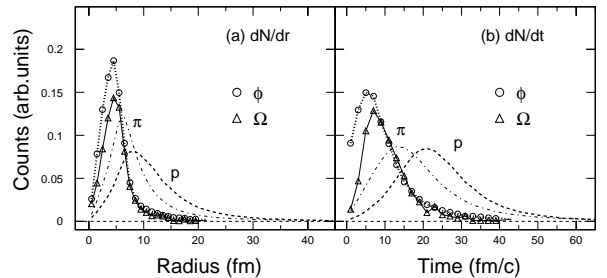


Figure 3: The RQMD transverse freeze-out radius (a) and freeze-out time (b) for charged pions (π), (anti-)protons (p), ϕ mesons (ϕ), and the multi-strange baryon Ω . The results shown are from 10% most central ($b < 3$ (fm)) $^{197}\text{Au} + ^{197}\text{Au}$ collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV. The normalization of the distributions is arbitrary.

is due to the small hadronic cross section of ϕ -mesons as implemented in RQMD. The ϕ -meson shows only little interaction in the hadron gas leading to an early freeze-out time at small transverse radius, as can be seen in Fig. 3. The ϕ -meson might freeze-out as soon as it is formed. Therefore, eventual collective motion of the ϕ -meson might have been dominantly built up during the pre-hadronic, or in other words, partonic stage. At the maximum SPS energy ($\sqrt{s_{\text{NN}}} \approx 17.2$ GeV), the multi-strange baryon Ω might be less sensitive to hadronic re-scattering [11]. It seems that multi-strange particles freeze-out earlier compared with non-strange ones. In order to identify and study partonic collectivity [22], a systematic study of the distributions of ϕ -mesons and other multi-strange particles, including both elliptical and radial flow, is essential.

In summary, we presented results of the RQMD transverse momentum distributions from central $^{197}\text{Au} + ^{197}\text{Au}$ collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV. We find that the measured mean transverse momentum of pions and protons are well reproduced by calculations with RQMD. The systematics of the mean transverse momentum indicates that the transverse expansion is important for collisions at RHIC. However, with copiously produced particles like pions, Kaons, and protons, it is not possible to determine if the collectivity is developed early or later dur-

ing the evolution of the system. Within the framework of RQMD, multi-strange particles decouple earlier from the system than other ones. We propose to study multi-strange and charmed-particle transverse momentum distributions in order to gain insight into partonic collectivity in high energy nuclear collisions.

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