PRODUCTION AND FLOW OF IDENTIFIED HADRONS AT RHIC*

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We review the production and flow of the identified hadrons at RHIC with main emphasis on the intermediate transverse momentum region ($p_{\rm T} \approx 2$–5 GeV/c). The goal is to unravel the dynamics of baryon production and resolve the anomalously large baryon yields and elliptic flow observed in the experiments.

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1. Introduction

This paper explores the relativistic heavy ion collisions at RHIC and the medium produced in these collisions using hadronic observables. Being most abundantly produced, hadrons define the bulk medium behavior, which is governed by soft, non-perturbative particle production. Analysis of identified hadron spectra and yield ratios allows determination of the kinetic and chemical properties of the system. Hydrodynamics models [1] have been successful in reproducing identified hadron spectral shapes and their characteristic mass dependence at low $p_{\rm T}$ as well as the azimuthal anisotropy of particle emission. Notably, in order to match the data the models require rapid equilibration of the produced matter and a QGP equation of state. The particle abundances also point to an equilibrated system and are well described by statistical thermal models [2]. The chemical freeze-out at $T_{\rm ch} \approx 170$ MeV is suggestive, as it is at the phase boundary of the transition between hadron gas and QGP, as predicted by lattice QCD calculations [3].

Above $p_{\rm T} \approx 2$ GeV/c, hard-scattering processes become increasingly important. After the hard-scattering, a colored object (the hard-scattered quark or gluon) traverses the medium produced in the collision and interacts strongly. As a result, it loses energy via induced gluon radiation. This

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phenomenon, known as jet-quenching, manifests itself as suppression in the yields of high-$p_{\rm T}$ hadrons, when compared to the production in pp collisions and weakening of the back-to-back angular correlations between the jet fragments. The yield suppression is measured in terms of the nuclear modification factor $R_{AA} = {\rm Yield}_{AA}/N_{\rm coll}/{\rm Yield}_{pp}$, where the number of binary nucleon–nucleon collisions, $N_{\rm coll}$, is introduced to account for the nuclear geometry. In this paper, we use the ratio $R_{\rm CP}$, which is obtained from the $N_{\rm coll}$ scaled central to peripheral spectra and carries similar information. Jet quenching was discovered at RHIC both in suppressed hadron production at high-$p_{\rm T}$ [4] ($R_{AA} < 1$) and in vanishing back-to-back jet correlations [5].

Another discovery, unpredicted by theory, is a large enhancement in the production of baryons and anti-baryons at intermediate $p_{\rm T} \approx 2$–5 GeV/c [6, 7], compared to expectations from jet fragmentation. This is in contrast to the suppression of π^0 [8]. In central Au + Au collisions the ratio $\overline{p}/\pi$ is of the order 1 — a factor of 3 above the ratio measured in peripheral reactions or in pp collisions. In this region of $p_{\rm T}$ fragmentation dominates the particle production in pp collisions. It is expected that fragmentation is independent of the colliding system — hence the large baryon fraction observed at RHIC comes as a surprise. At RHIC, the medium influences the dynamics of hadronization resulting in enhanced baryon production but the exact mechanism is not yet completely understood. This paper reviews the latest experimental results relevant to this subject.

2. Radial flow at intermediate $p_{\rm T}$

The most common conjecture which is invoked to explain the large $\overline{p}/\pi$ ratios observed by PHENIX [7] is the strong radial flow that boosts the momentum spectra of heavier particles to high $p_{\rm T}$. In this scenario, the soft processes dominate the production of (anti)protons at 2–4.5 GeV/c, while the pions are primarily produced by fragmentation of hard-scattered partons. In Fig. 1 we compare the 10% central spectra of $\pi^{\pm}, K^{\pm}$, p, and $\overline{p}$ to a hydrodynamics model [9] that has been fitted to the data. The free parameters in the model are the kinetic freeze-out temperature $T_{\rm fo}$, the transverse flow velocity $\beta_{\rm T}$ and the absolute normalization. The line drawn through the ϕ-meson spectrum is the model's prediction obtained after fitting all other particle species. We see that: (1) Hydrodynamics gives a good description of the p and $\overline{p}$ spectral shapes up to ≈ 3 GeV/c, and (2) the ϕ-meson spectrum can be described by the same parameter set as the protons. For lighter particles, the deviation from hydrodynamics happens at lower $p_{\rm T}$. These results may lead to the conclusion that the enhanced $\overline{p}/\pi$ ratio is a mass effect and the intermediate $p_{\rm T}$ (anti)protons are primarily produced in soft processes. We now examine the scaling of the yields in

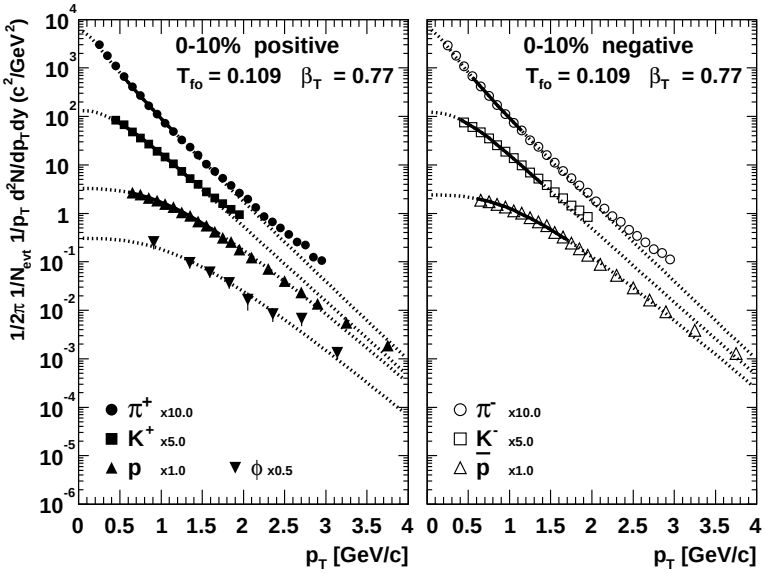


Fig. 1. Transverse momentum spectra of $\pi^{\pm}, K^{\pm}$, and $p, \overline{p}$ and hydrodynamical fit results for 0–10% central Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [10]. The p_{T} ranges for the fit are indicated by the solid lines, while the dashed lines show the extrapolated predictions for each particle species. The ϕ-meson spectrum, not included in the fit, is compared to the model's prediction.

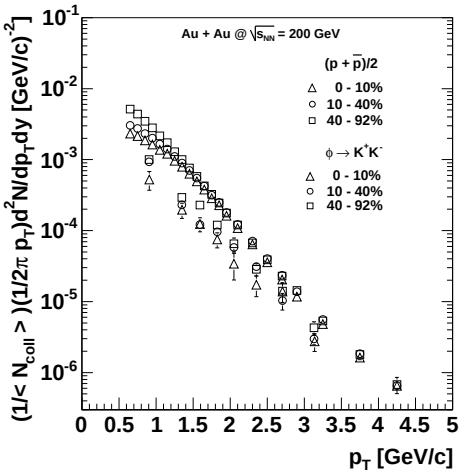


Fig. 2. N_{coll}-scaled transverse momentum spectra of $(p + \overline{p})/2$ and ϕ-mesons for three different centrality classes. High-p_{T} baryon yields scale with N_{coll}, while no scaling is observed for ϕ-mesons [10].

different centrality classes. We expect that for soft production the yields will scale as the number of nucleons participating in the collision, while for hard processes the scaling is with $N_{\rm coll}$. In Fig. 2 the $p_{\rm T}$ distributions for (anti)protons and ϕ are scaled down each by their respective $N_{\rm coll}$. To isolate mass effects from baryon/meson effects we compare a heavy meson to the protons. The result is rather surprising. At intermediate $p_{\rm T}$ the $p + \overline{p}$ yields scale with $N_{\rm coll}$ as expected for hard processes. The ϕ yields do not scale. Although the shape of the $p + \overline{p}$ and ϕ spectra is the same and is well reproduced by hydrodynamics, the absolute yields for ϕ grow slower with centrality. When the central and peripheral yields are used to evaluate the nuclear modification factor (Fig. 3), the (anti)protons show no suppression ($R_{\rm CP} \approx 1$), while the ϕ are suppressed similar to π^0. This result rules out the radial flow (and the mass) as the sole factor that is responsible for the baryon enhancement. The similarity in the centrality dependence of ϕ and π production suggests an effect related to the number of constituent quarks rather than the mass. The STAR experiment also observed a clear baryon/meson distinction in $R_{\rm CP}$ of K^*, K^0_s, Λ, and Ξ [12].

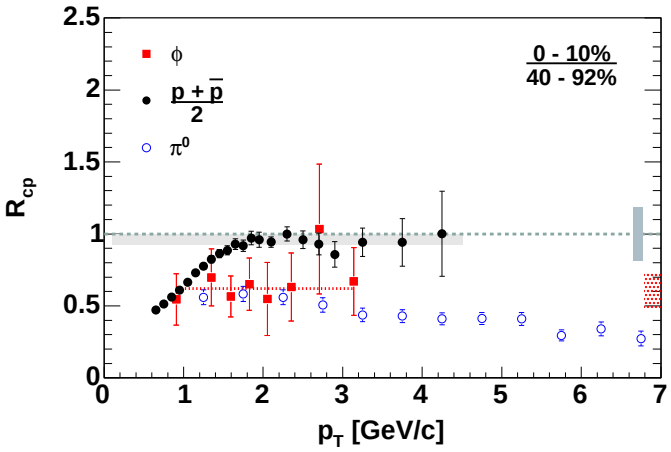


Fig. 3. The nuclear modification factor, $R_{\rm CP}$, of ϕ, $p + \overline{p}$ and π^0 measured by PHENIX in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV [10, 11].

3. Recombination and empirical scaling of elliptic flow

Recently, several quark recombination models [13–15] have been proposed to resolve the RHIC baryon puzzle. In the dense medium produced in central Au + Au collisions, recombination of quarks becomes a natural hadronization mechanism. When produced from the same underlying thermal quark distribution, baryons get pushed to higher $p_{\rm T}$ than mesons due

to the addition of quark momenta. At intermediate p_{T} recombination wins over fragmentation for baryons, while mesons are still dominated by fragmentation. After fitting the inclusive hadron spectra to extract the thermal component, the models are able to reproduce a large amount of data on identified particle spectra, particle ratios and nuclear modification factors. The most spectacular success of the recombination models comes from the comparison with the data on elliptic flow. At low-p_{T} hydrodynamics describes both the magnitude and the mass dependence of v_2. However, at $p_{\mathrm{T}} > 2$ GeV/c the mass ordering of v_2 changes, namely: $v_2(p) > v_2(\pi)$ [16] and $v_2(\Lambda) > v_2(K_{\mathrm{s}})$ [12]. In addition, the size of the signal is too big to be explained by asymmetric jet absorption [17]. The recombination models solve the problem by assigning the elliptic flow signal to the quarks, instead of the hadrons. Then the baryon/meson split in v_2 is naturally explained. It has been demonstrated empirically, that the flow per quark is universal. Recent results from the STAR [18] experiment that include the measurement of multi-strange baryons are shown in Fig. 4. A clear baryon/meson difference is observed in the data at $p_{\mathrm{T}} > 2$ GeV/c. The results from a typical hydrodynamic model calculations [19] are shown with a band. After re-scaling of both axes in Fig. 4 to represent the quark flow, the data falls on a universal curve, as demonstrated in Fig. 5.

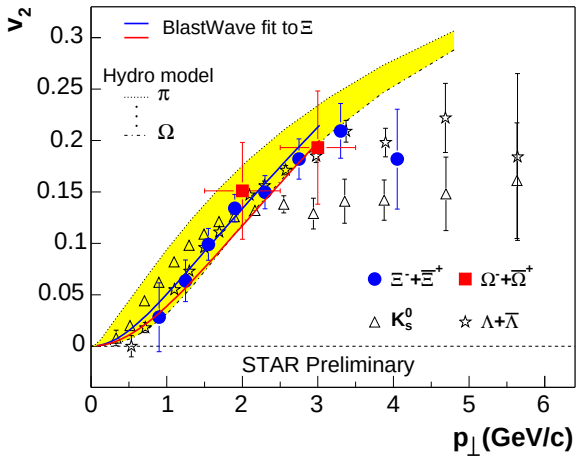


Fig. 4. $v_2(p_{\mathrm{T}})$ for $\Xi^- + \overline{\Xi}^+$, $\Omega^- + \overline{\Omega}^+$, K^0_{S} and $\Lambda + \overline{\Lambda}$ for minimum bias Au + Au collisions [18]. The curves show the results from hydrodynamics calculations.

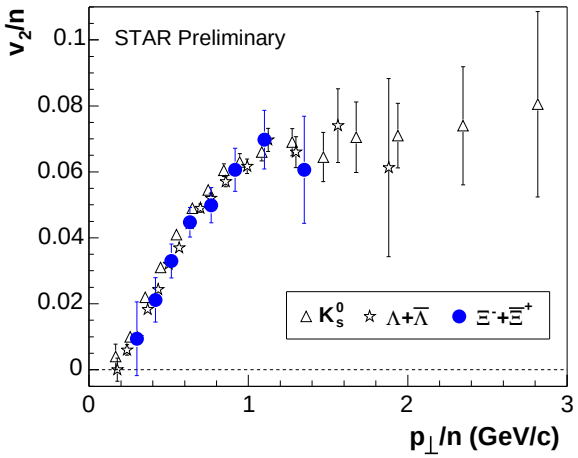


Fig. 5. v_2/n as a function of $p_{\rm T}/n$ for $K^0_{\rm S}$, $\Lambda+\overline{\Lambda}$ [12] and $\Xi^-+\overline{\Xi}^+$, where n is the number of constituent quarks for each particle. (Figure taken from [18].)

4. Jet correlations with leading baryons or mesons

The recombination models resolve most of the baryon/meson effects observed in the data. However, from spectra, particle ratios and elliptic flow it is difficult to infer whether the recombining quarks come from the thermal bath (soft processes) or from hard-scattering. To unravel the nature of the baryon enhancement and to test the recombination approach, the PHENIX experiment examined the two-particle angular correlations with identified meson or baryon trigger particle [20]. The momentum of the triggers was chosen to be in the range of $p_{\rm T}$ where baryon/meson differences are observed ($2.5 < p_{\rm T} < 4$ GeV/c). For both types of trigger, clear jet-like angular correlations were observed both on the same side of the trigger and at 180°. This result shows that both mesons and baryons have a significant hard-scattering component at intermediate $p_{\rm T}$, although the $\overline{p}/\pi$ ratios are dramatically different from fragmentation in the vacuum. In order to quantify the similarity between baryon and meson triggered correlations, the yield of associated particles is integrated at the near-side and the away side peaks. The results for different centrality classes and colliding systems are shown in Fig. 6. There is an increase in partner yields in mid-central Au + Au compared to the d + Au and $p+p$ collisions. In Au + Au collisions, the near side yield per *meson* trigger remains constant as a function of centrality, whereas the near-side yield per *baryon* trigger decreases in the most central collisions as expected if a fraction of the baryons were produced by soft processes such as recombination of thermal quarks. The dashed line in Fig. 6 represents an upper limit to the centrality dependence of the jet partner yield from thermal recombination. The data clearly disagree with

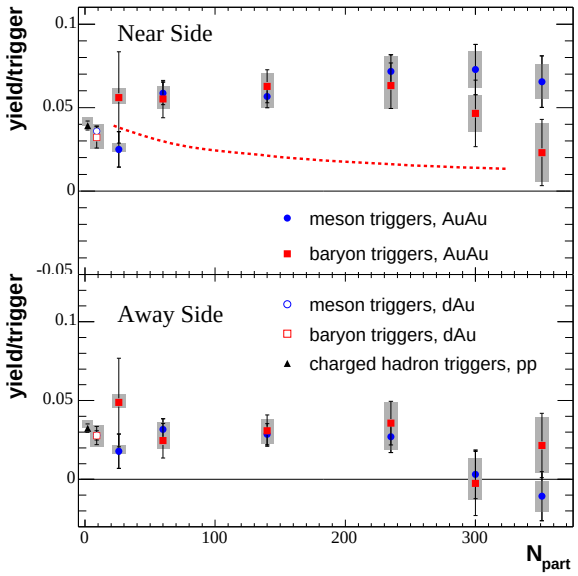


Fig. 6. Yield per trigger for associated charged hadrons between $1.7 < p_{\mathrm{T}} < 2.5$ GeV/c for the near- (top) and away- (bottom) side jets [20]. The dashed line (top) represents an upper limit of the centrality dependence of the near-side partner yield from thermal recombination.

both the centrality dependence and the absolute yields of this estimation, indicating that the baryon excess has the same jet-like origin as the mesons, except perhaps in the highest centrality bin. The bottom panel of Fig. 6 shows the conditional yield of partners on the away side. It drops equally for both trigger baryons and mesons going from $p+p$ and d + Au to central Au + Au, in agreement with the observed disappearance [5] and/or broadening of the dijet azimuthal correlations. It further supports the conclusion that the baryons originate from the same jet-like mechanism as mesons.The description of the data in the pQCD framework would require an in-medium modification of the jet fragmentation functions. For recombination models, the experimental results imply that shower and thermal partons have to be treated on an equal basis [14].

5. Summary

We reviewed the results on hadron production and flow in relativistic heavy ion collisions at RHIC. The production mechanisms at low-p_{T} and high-p_{T} are relatively well understood in terms of soft and hard processes, respectively. The intermediate p_{T} region ($2 < p_{\mathrm{T}} < 5$GeV/c) is marked by

a number of puzzling experimental observations and most notably, by the baryon excess over the expectation from vacuum fragmentation functions. By comparing spectra and centrality scaling of (anti)protons and ϕ-mesons, we established that the excess of anti-protons with respect to pions is not due to the larger mass of the anti-proton, but is related to the number of constituent quarks. The recombination models get a beautiful confirmation in the empirical scaling relation of the elliptic flow results. Jet-correlations with trigger baryons or mesons show a similar hard-scattering component in both. This observation is also in line with the $N_{\rm coll}$ scaling observed in the yields of protons and anti-protons. However, it implies that protons originate from partons that experience little or no energy loss, while pions come from partons that have suffered large energy loss. This result is conceptually difficult, unless baryons and mesons have a very different formation time and thus — the original partons have different time to interact with the medium. Recombination models which combine hard-scattered partons with thermal ones give the most likely explanation of the experimental results as a whole. The baryon excess is clearly an effect of the medium produced in Au + Au collisions and maybe, through the comparison with recombination models, gives evidence for its partonic nature.

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