Hadron Production at RHIC: Recombination of Quarks

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Abstract. We discuss quark recombination applied to the hadronization of a quark gluon plasma. It has been shown that the quark recombination model can explain essential features of hadron production measured in high energy heavy ion collisions.

In this manuscript we discuss recent progress in our understanding of hadronization in high energy nuclear collisions as they are routinely studied at the Relativistic Heavy Ion Collider (RHIC). The RHIC program with its four experiments is committed to create a quark gluon plasma (QGP) in collisions of Au nuclei at an center of mass energy $\sqrt{s} = 200$ GeV per nucleon pair. The energy densities reached on time scales of a few fm/$c$ after the collision are large enough to achieve a phase transition to a deconfined phase of quarks and gluons at a phase transition temperature of roughly 170 MeV [1].

One of the most exciting new discoveries at RHIC was jet quenching [2]. At RHIC energies hard QCD processes take place besides the formation of a deconfined medium. In those hard processes quarks and gluons with large transverse momentum $P_T$ relative to the beam axis (i.e. $P_T > 1$ GeV/$c$) are created. In $e^+ + e^-$ or $p + p$ collisions these hard processes are taking place in the vacuum and the partons fragment into a jet of hadrons. In Au+Au collisions these partons are propagating and fragmenting in the surrounding deconfined QCD medium. It was predicted that the strong interaction with the medium should lead to considerable energy loss of these partons. Indeed, it was found at RHIC that the production of pions with transverse momenta $> 1$ GeV/$c$ is suppressed by a factor 4 to 5 compared with a naive scaling from $p + p$. This observation confirms the existence of a very dense phase of gluons.

However, there is a puzzle connected to this. Jet quenching seems to be absent for protons, antiprotons and Lambdas, which is at odds with the interpretation of energy loss on a parton level [3, 4, 5]. Also the proton/pion ratio was measured to be about unity for $P_T$ between 1.5 and 4 GeV/$c$ [3]. The value predicted by perturbative QCD and fragmentation functions would be between 0.2 and 0.3. From these observation one can conclude that we have to give up the picture of perturbative hadron production for $P_T$ at least up to 4 GeV/$c$ in Au+Au collisions. Fragmentation describes how a single parton in the vacuum hadronizes. It has to radiate gluons which subsequently split into quark-antiquark pairs. Hadronization can only start once sufficient quark-antiquark pairs are available to turn into valence quarks of hadrons. In a dense medium, enough partons are already there to start with and could just recombine or coalesce into hadrons: three quarks into a baryon, a quark-antiquark pair into a meson. Several groups...
have suggested that recombination occurs at RHIC up to relatively large transverse momenta [6, 7, 8].

In the recombination model the yield of hadrons from a given parton system can be calculated starting from a convolution of Wigner functions [7]. For a meson with valence (anti)quarks \( a \) and \( b \) we have

\[
\frac{d^3 N_M}{d^3 P} = \sum_{a,b} \int \frac{d^3 R}{(2\pi)^3} \int \frac{d^3 q d^3 r}{(2\pi)^3} W_{ab} \left( R - \frac{r}{2}, \frac{P}{2} - q; R + \frac{r}{2}, \frac{P}{2} + q \right) \Phi_M(r, q). \tag{1}
\]

Here \( W_{ab} \) is the 2-particle Wigner function for partons \( a \) and \( b \) and \( \Phi_M \) is the Wigner function of the meson. The sum runs over all possible parton quantum numbers. We note that recombination is dominated by the lowest state in the Fock expansion of the hadron, i.e. the valence quarks. For practical purposes the parton Wigner function is usually approximated by a product of single particle phase space distributions \( W_{ab} = w_a w_b \). Several implementations of recombination have been discussed in the literature [7, 8], see [9] for a review.

One can compare the yield of fragmentation and recombination starting from different parton spectra. The result of this competition is rather surprising. Thermal, or at least exponential, parton spectra \( w \sim e^{-P/T} \) play a special role. Recombination on such an exponential parton distribution leads to an exponential hadron distribution with the same slope since \( w_a w_b \sim e^{-x P/T} e^{-(1-x) P/T} = e^{-P/T} \) where \( x \) gives the momentum fraction of parton \( a \). Therefore recombination is more effective than fragmentation on any thermalized parton ensemble. On the other hand one can show that a power-law parton spectrum favors fragmentation at least for large \( P_T \), in accordance with perturbative QCD. It is only safe to apply eq. (1) when the energies of the partons inside the hadron are dominated by their longitudinal momenta.

Calculations at RHIC energies recombine a thermalized system of constituent quarks with a temperature \( T \) around the phase transition temperature and strong radial flow. To describe the high-\( P_T \) spectrum of hadrons this has to be supplemented by a pQCD calculation using
Figure 2. Elliptic flow $v_2$ for $\pi^+$, $p$, $K^*_0$ and $\Lambda$ as a function of $P_T$ scaled by the number of valence quarks $n$ vs $P_T/n$. The data follows a universal curve, impressively confirming the quark scaling law predicted be recombination. Deviations for the pions are discussed in the text. Data are taken from PHENIX ($\pi^+$, $p$) [13] and STAR ($K^*_0$, $\Lambda$) [5].

Elliptic flow has long been observed in heavy ion collisions. In collisions at finite impact parameter, the shape of the overlap zone of both nuclei is not azimuthally symmetric around the beam axis. This spatial anisotropy is converted into an azimuthal anisotropy of the measured particle spectra. The second azimuthal Fourier coefficient $v_2$ in the expansion $dN/d\phi = N[1 + \sum_n 2v_n \cos(n\phi)]$, where $\phi$ is the azimuthal angle, is also called elliptic flow. Let us assume the parton phase exhibits an elliptic flow $v_2^p(p_T)$ as a function of parton momentum $p_T$. Recombination predicts that the elliptic flow of any hadron species is given by [11, 7]

$$v_2(p_T) = n v_2^p(p_T/n).$$

Here $n$ is the number of valence quarks for the hadron. Hence there should be another striking difference between mesons (scaling with $n = 2$) and baryons (scaling with $n = 3$). Different mesons should follow the same scaling law, even if the masses of the mesons are very different.

Fig. 2 shows the measured elliptic flow $v_2$ for several hadron species in a plot with scaled axes $v_2/n$ vs $P_T/n$. All data points (with exception of the pions) fall on one universal curve. This is a an impressive confirmation of the quark scaling rule and the entire recombination picture. The pions are shifted to lower $P_T$, because most of them are from secondary decays of hadrons [12]. We note that the scaled elliptic flow in Fig. 2 is equivalent to the parton elliptic flow. This would be the first direct observation of a non-trivial observable in the parton phase. As an immediate consequence we conclude that strange quarks have the same elliptic flow as light quarks.

We can rewrite the scaling for elliptic flow in the spirit of a classical quark counting rule (2)

$$\frac{v_2^M(2p)}{v_2^B(3p)} = \frac{2}{3}$$

where the superscripts $M$ and $B$ stand for the elliptic flow of a meson and a baryon respectively. This quark counting rule is a clear hint that quarks are relevant degrees of freedom at RHIC.
Furthermore, elliptic flow is an observable to describe collective behavior. This implies that we created bulk matter with subhadronic degrees of freedom. Therefore, this discovery could be a very important step to prove the creation of a quark gluon plasma in Au+Au collisions at RHIC.

Recombination has been proven to be a valid description of hadron production in high energy heavy ion collisions at intermediate $P_T$. Hadron spectra, hadron ratios, nuclear modification factors and elliptic flow at can be explained. The predictive power of recombination lies in the fact that a consistent description of all hadron species has been achieved with only one universal parametrization of the parton phase in terms of temperature, radial and elliptic flow and volume. The quark counting rule for elliptic flow, impressively confirmed by experiment, might prove to be an important cornerstone to make the case for the quark gluon plasma.

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