Studying nuclear matter created in p+p, d+Au and Au+Au collisions using charged kaons

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Abstract. Kaons, as the main carriers of strangeness, make for an important probe of the medium produced in relativistic heavy ion collisions. By topologically reconstructing the charged kaons, we reach high transverse momentum limits not presently accessible with the traditional reconstruction methods. We present recent results on nuclear modification factors involving charged kaons from three collision systems: p+p, d+Au and Au+Au at 200GeV center of mass energy. A comparison to other strange mesons and baryons will be made and conclusions on medium properties, particle production mechanisms, initial and final state effects will be presented.

1. Introduction

Some of the questions that the RHIC program at Brookhaven National Laboratory tries to answer are: what are the properties (density, degrees of freedom etc) of the medium created after colliding relativistic heavy ions, what is the nature of the hadronization mechanism and is it unique process independent of transverse momentum? The answers have to take into account the fact that the measured observables are influenced by both initial state (e.g. multiple scattering, gluon saturation) and final state (partonic or hadronic interactions) effects. In order to disentangle these effects, comparisons to simpler baseline systems (d+Au and p+p) are performed and some of them are presented in this paper.

A useful tool that has been applied to these studies is the Nuclear modification factor \( R_{AB} \):

\[
R_{AB}^{h} = s \frac{1}{<N_{binary}^{AB}>} \frac{d^{2}N_{AB}^{h}}{d^{2}N_{pp}^{h}} 
\]

where \( d^{2}N^{h} \) is the hadron differential yield and \( <N_{binary}^{AB}> \) is the mean number of binary collisions. It is thought that for \( p_{T} > 2 \text{ GeV}/c \), particle production should scale with the number of binary collisions and hence \( R_{AB}^{h} \approx 1 \). An \( R_{AB}^{h} < 1 \) is indicative of in-medium energy loss whilst an \( R_{AB}^{h} > 1 \) is traditionally attributed to soft parton scattering prior to the hard collision (Cronin effect) [1]. An alternative measurement that has been applied to the data is the ratio of spectra in central to peripheral collisions, \( R_{CP} \). The assumption made is that the information provided by either ratio is consistent, as long as the peripheral Au+Au, d+Au and p+p data are similar. This is a reasonable hypothesis as a dense medium is presumably not created in any of these systems, which could cause many hadronic or partonic re-scattering in the final state.
Previous results on unidentified spectra have shown $R_{AA}^{RH} < 1$ in central Au+Au collisions and $R_{AB}^{RH} > 1$ in minimum bias d+Au collisions [2]. Models based on LO pQCD calculations interpreted the data as medium induced jet quenching in central Au+Au collisions and initial state Cronin effect in d+Au data [3, 4]. These first inclusive hadron results pointed to (string) fragmentation as the hadronization mechanism for $p_T > 2\text{GeV/c}$.

However, further studies using identified particle distributions revealed new phenomena. The first measurements of identified particle $R_{CP}$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV showed differences in the level of suppression between kaons and the $\Lambda$ in the intermediate transverse momentum region between 2 and 6 GeV/c [9]. These measurements were inconsistent with a simple model of jet quenching in the medium and required further explanation. Further measurements of $R_{CP}$ for other particles ($K^{*}$, $\Xi$ and $\Omega$) showed that this observed effect was not dependent on the particle mass, but rather on the particle species: mesons exhibited a different level of suppression to baryons [10].

In order to explain this baryon-meson anomaly a number of recombination models postulated that baryons are formed from three, and mesons from two, coalescing quarks respectively [8]. Therefore, assuming the same partonic $p_T$ in a thermal partonic medium, the baryons will be pushed further in $p_T$ compared to mesons and their suppression will occur later in transverse momentum.

In this paper we present the $R_{AuAu}$ and $R_{dAu}$ measurements for identified baryons and mesons as obtained by the STAR Collaboration.

2. Data analysis

The experimental results presented were obtained using events collected by the STAR experiment during the $\sqrt{s_{NN}} = 200$ GeV runs in 2001 (Au+Au and p+p) and 2003 (d+Au). The majority of the particles used are reconstructed via their decay products, either through topological cuts ($\Lambda$, $\Xi$, $K_{S}^{0}$, $K^{\pm}$, $\Omega$, $\Xi$, $\Sigma$ and $\Xi$) on tracks measured in the Time Projection Chamber (TPC) [11] or through an event mixing technique [12]. The proton $R_{AuAu}$ is obtained by combining information from the Time of Flight (TOF) and the Cherenkov (RICH) detectors [11].

Charged kaon decays are detected through their characteristic ‘kink’ topology: $K^{\pm} \rightarrow \mu^{\pm}\nu(64\%)$, $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}(21\%)$ [13]. The charged parent (kaon) decays to a neutral daughter (not detected) and a charged daughter with the same sign. Therefore, the kaon identification process reduces to the finding of ‘bent’ tracks (kinks) in the TPC. Geometrical cuts and kinematical constraints are applied to the candidates in order to reduce the background and isolate the signal. In these datasets, the transverse momentum limitation is dictated by statistics only: 3 GeV/c in p+p, 4 GeV/c in d+Au and 5 GeV/c in Au+Au.

3. Results

In Fig. 1 the $R_{AuAu}$ for different baryons and mesons is presented as a function of $p_T$ for central Au+Au collisions. The $R_{meson}^{AuAu}$ is consistent with the $R_{CP}^{meson}$, and the $R_{AuAu}$ and $R_{CP}$ of the proton are also in agreement [5]. However, for the strange and multi-strange baryons, the $R_{AuAu}$ shows the opposite effect to the $R_{CP}^{baryon}$ results [10]: it is not reduced but increased with respect to binary scaling in the intermediate ($2$ to $6$ GeV/c) $p_T$ region. Moreover, there seems to exist an ordering, which follows the strange quark content: $\Xi$ hyperons ($\text{strangeness S=-2}$) are enhanced more than $\Lambda$ hyperons ($\text{S=-1}$) which are in turn enhanced more than protons ($\text{S=0}$).

A first attempt at determining $R_{dAu}$ is shown in Figure 2. The present level of uncertainties in the d+Au analysis do not allow us to draw significant conclusions about a possible strangeness ordering also in d+Au. However, we can affirm that the baryon-meson difference observed in Au+Au is present also in d+Au but at a smaller level which cannot account for the meson-baryon differences seen in $R_{CP}^{AuAu}$. 
4. Discussion

Though the experimental results on $R_{CP}$ point to the validity of the quark coalescence picture, several other models offer a different explanation to describe both the central to peripheral ratio and the central to p+p ratio [15, 14]. In particular, HIJING/Bv2.0 attributes the meson-baryon separation to a different $p_T$ ‘kick’ for di-quarks than for quarks and to the presence of an additional baryon production mechanism (string junctions loops) which has an increasing contribution from p+p to d+Au to Au+Au collisions [14]. In the same string fragmentation scenario, the presence of ‘strong color field’ effects influence the strange baryon production and produces the strangeness ordering in the $R_{AA}$ plot.

In addition to these hadronization scenarios, other effects might influence the Au+Au to p+p spectra ratios. In particular, if canonical suppression dominates the strange baryon production in p+p collisions but not in peripheral Au+Au collisions [16], then a plausible reason for the $R_{AA}$ increase with respect to binary scaling is not only an enhancement of the yield in central Au+Au collisions, but a suppression of the yield in p+p collisions. It was shown that this suppression will increase as a function of strangeness content for baryons [16], and therefore it should lead to larger differences between $R_{CP}$ and $R_{AA}$ for multi-strange baryons than for singly strange or non-strange baryons.

Figure 1. $R_{AuAu}$ for mesons(left), baryons (right) and inclusive charged hadrons (dashed line). Statistical errors only are shown.

Figure 2. $R_{dAu}$ for mesons(left), baryons (right) and inclusive charged hadrons (dashed line). Statistical errors only are shown.
5. Summary

We have presented nuclear modification factors $R_{AuAu}$ and $R_{dAu}$ for identified hadrons, as measured by the STAR Collaboration. A difference between baryons and mesons is observed, similar to the one measured in the Au+Au central to peripheral ratios ($R_{CP}$). However, the $R_{baryon}^{AuAu}$ is reduced in comparison to binary scaling at all $p_T$ in Au+Au collisions, whereas the $R_{baryon}^{AuAu}$ in the intermediate $p_T$ region is increased for strange baryons. In addition, the $R_{baryon}^{AuAu}$ values show an ordering according to the baryon strangeness content, a feature which was not found in the $R_{baryon}^{CP}$ values. Less of a difference is observed between $R_{CP}$ and $R_{AuAu}$ in the case of mesons (strange and non-strange) and non-strange baryons. The meson-baryon differences are also present in $R_{dAu}$ but at a smaller level which cannot account for the meson-baryon differences seen in $R_{CP}^{AuAu}$.

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