Effect of final state interactions on particle production in $d+Au$ collisions at RHIC

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Abstract

We show that particle species dependence of enhanced hadron production at intermediate transverse momentum ($p_T$) for $d+Au$ collisions at RHIC can be understood in terms of the hadronic rescatterings in the final state. A multiphase transport model (AMPT) with two different hadronization mechanisms: string fragmentation or parton coalescence, is used in our study. When the hadrons are formed from string fragmentation, the subsequent hadronic rescatterings will result in particle mass dependence of nuclear modification factor $R_{CP}$, which is consistent with the present experimental data. On the other hand, in the framework of parton coalescence, the mass dependence disappears and the strangeness plays an important role. Both mechanisms failed to reproduce the $p_T$ dependence of $R_{CP}$ of pion, indicating that initial-state effects might be also important in such collisions.

Keywords: Nuclear modification factor, hadronization mechanisms, hadronic rescatterings

1. Introduction

The Cronin effect, which refers to the enhanced hadron production at intermediate transverse momentum ($p_T$) with increasing target nucleus size in proton-nucleus (pA) collisions, was first observed by Cronin \textit{et al.} \cite{1,2} in 1975 at center of mass energy $\sqrt{s_{NN}} = 27.4$ GeV. Recent experimental data in $d+Au$ collisions from RHIC have shown that similar effect exists at higher collision energy ($\sqrt{s} = 200$ GeV) \cite{3,4}. An adequate understanding of the Cronin effect becomes especially important for making reliable theoretical interpretations of the observations in heavy ion collisions at RHIC, in which the quark-gluon plasma (QGP) is thought to be created \cite{5}. Traditional explanations of the Cronin effect all involve multiple scattering of incoming partons that lead to an enhancement at intermediate $p_T$ \cite{6,11}. The models can reproduce the observed centrality dependence for pions very well. However, none of these initial-state models would predict a species-dependent Cronin effect, as initial state parton scattering precedes fragmentation into the different hadronic species \cite{4}. This indicates possible final-state interactions (FSI) would possibly contribute to the Cronin effect.

Recently, Hwa and Yang \cite{12} demonstrated the recombination of soft and shower partons in the final state could explain the mass dependent Cronin effect. This model do predict a larger enhancement for protons than for pions at $1 < p_T < 4$ GeV/c. However, the inclusion of recombination from deconfined partons requires a high energy density in initial state, which may not be justified in $d+Au$ collisions. An alternate way for hadronization is string fragmentation \cite{13-15}. In this scenario, hadrons are formed from the decays of excited strings, which result from the recombination of energetic minijet partons and soft strings that produced from initial soft nucleon-nucleon interactions. After the hadronization, the followed rescatterings between formed hadrons or between formed hadrons and nucleon spectators should also be taken into account.

In this paper we study quantitatively how the two different hadronization mechanisms (string fragmentation and parton coalescence) and the followed final state interactions would contribute to the nuclear modification factors in $d+Au$ collisions at $\sqrt{s} = 200$ GeV. A multiphase transport model (AMPT) \cite{14,15} with two versions: default (hadronization from Lund string fragmentation, mainly hadronic rescatterings in the final state, version 1.11) and string melting (hadronization from quark coalescence, version 2.11) are used to study the later-stage effect. The final state hadronic and/or partonic interactions are included in the calculations. Quark transverse momentum kick due to multiple scatterings are treated in the same way as in Ref. \cite{13}. To have a clean test of final state interactions, we assume no quark intrinsic $p_T$ broadening due to initial multiple parton scattering \cite{8}, and see how the final state interactions would contribute to the Cronin effect observed. We show that recent data on particle species dependence of central-to-peripheral nuclear modification factor $R_{CP}$ midrapidity for $d+Au$ collisions at RHIC can be understood in terms of the hadronization from string fragmentation and the followed hadronic rescatterings in the final state.

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2. The AMPT model

The AMPT model [14,15] is a hybrid model that consists of four main components: the initial conditions, the partonic interactions, conversion from the partonic to the hadronic matter, and the hadronic interactions. The initial conditions, which include the spatial and momentum distributions of hard mini-jet partons and soft string excitations, are obtained from the Hijing model (version 1.383 for this study). One uses a Woods-Saxon radial shape for the colliding gold nuclei and introduces a parameterized nuclear shadowing function that depends on the impact parameter of the collision. The ratio of quark structure function is parameterized as the following impact-parameter-dependent but $Q^2$- (and flavor)-independent form [14]

$$R_A(x, r) \equiv \frac{f_A^d(x, Q^2, r)}{A f^d(x, Q^2)} = 1 + 1.19 \ln^{1/6} A (x^3 - 1.2 x^2 + 0.21 x)$$

$$- [\alpha_A(r) - 1.08 (A^{1/3} - 1) \sqrt{\frac{\ln (A + 1)}{A + 1}}] e^{-x^2/0.01},$$

(1)

where $x$ is the light-cone momentum fraction of parton $a$, and $f^d$ is the parton distribution function. The impact-parameter dependence of the nuclear showing effect is controlled by

$$\alpha_A(r) = 0.133 (A^{1/3} - 1) \sqrt{1 - r^2/R_0^2},$$

(2)

with $r$ denoting the transverse distance of an interacting nucleon from the center of the nucleus with radius $R_0 = 1.2A^{1/3}$. The structure of deuteron is described by the Hulthen wave function. Scatterings among partons are modeled by the Zhang’s parton cascade (ZPC) [16], which at present includes only two-body elastic scatterings with cross sections obtained from the pQCD with screening masses. In the default AMPT model, after partons stop interacting, they recombine with their parent strings, which are produced from initial soft nucleon-nucleon interactions. The resulting strings are converted to hadrons using the Lund string fragmentation model. In case of string melting, the produced hadrons from string fragmentation, are converted instead to their valence quarks and antiquarks. The followed partonic interactions are modeled by ZPC. After the partons freeze out, they are recombined into hadrons through a quark coalescence process. The dynamics of the subsequent hadronic matter is described by a hadronic cascade, which is based on a relativistic transport model (ART). Final hadronic observables including contributions from the strong decays of resonances are determined when the hadronic matter freezes out.

3. Results

We learn that Lin and Ko have done a nice study [15] on global properties of deuteron-gold collisions with default AMPT model, which shows good agreement with later experimental data [17,18]. Their study on nuclear effects is up to $p_T = 2$ GeV/c. Here we focus on the intermediate to higher $p_T$ range where the Cronin effect exists. We study the deuteron-gold collisions at $\sqrt{s_{NN}} = 200$ GeV. The string fragmentation parameters are chosen to be the same as in Ref. [15]. The partonic scattering cross section is chosen to be 3 mb. The events are separated into different centrality bins using the number of participant nucleons suffering inelastic collisions. Fig. 1 shows the mid-rapidity ($|y| < 0.5$) transverse momentum spectra of pions, kaons, protons and $\phi$ mesons in “minimum bias” $d+Au$ collisions from default AMPT (solid line) and string melting AMPT (dashed line) versus data from STAR Collaboration (statistical error only) [3,19]. It is seen that both default and string melting AMPT can reproduce the $\pi^+$ and $K^+$ spectra well. For proton and antiproton production, the default version works well for $p_T > 1$ GeV/c, but underestimates the low $p_T$ proton and antiproton yields. The string melting version underestimates the proton and antiproton production in the whole $p_T$ range. For $\phi$ meson spectrum, the default version works well in the whole $p_T$ range, while the string melting one overestimates the low $p_T$ $\phi$ meson yields in the “minimum bias” $d+Au$ collisions.

Figure 1: Transverse momentum spectra of mid-rapidity ($|y| < 0.5$) pions, kaons, protons and $\phi$ mesons in “minimum bias” $d+Au$ collisions from default AMPT (solid lines) and string melting AMPT (dashed lines) versus data from STAR Collaboration (statistical error only) [3,19].

Figure 2: (Color online) (a) $R_{CP}$ for $\pi^+$, $K^-$, $\bar{p}$, $\phi$, $\Xi^+$ in $d+Au$ $\sqrt{s_{NN}} = 200$ GeV collisions from default AMPT without final state interactions included. (b) Kaon and $\Lambda$ rapidity distribution in “minimum bias” $d+Au$ collisions from default AMPT without final state interactions included. (c) quark ($u$, $d$, $s$, and $\bar{s}$) rapidity distribution before coalescence in “minimum bias” $d+Au$ collisions from string melting AMPT.
To study the final state effect on the nuclear modification factor $R_{CP}$, we first calculate the $R_{CP}$ (0-20% / 40-100% centrality) of different hadrons without including the final state hadronic interactions and resonance decays in the default AMPT. The $R_{CP}$, which compares particle yield from central collisions to that of peripheral collisions, is defined as the ratio of particle yields in central collisions over those in peripheral ones scaled by number of inelastic binary collisions $N_{bin}$, that is,

$$R_{CP} = \frac{[dN/(N_{bin} pT dpT)]_{central}}{[dN/(N_{bin} pT dpT)]_{peripheral}}$$

(3)

Here we use the same $N_{bin}$ value as STAR Collaboration at the corresponding collision centrality. One can see in Fig. 2(a) that there are only slight differences for the $R_{CP}$ of different particle species. This is because hadrons are produced from string fragmentation in the Lund model, and the fragmentation patterns for different particle species in central collisions and in peripheral collisions are set to be the same. We note that the $R_{CP}$ of proton and $\Lambda$ would be larger due to the associate production $N+N \rightarrow N+\Lambda+K^+$ from initial-state multiple scatterings in the gold beam direction ($y < 0$) at large rapidity, as shown in Fig. 2(b) the enhanced production of $\Lambda$ and $K^+$ in “minimum bias” $d+Au$ collisions. Some of the particles are scattered into mid-rapidity region. The strange quark enhancement in the large rapidity region (gold beam direction) will cause the corresponding increase of $\bar{s}$ quark at other rapidity regions due to net strangeness conservation. This is shown in Fig. 2(c): the quark rapidity distribution before coalescence in “minimum bias” $d+Au$ collisions from the string melting AMPT.

Figure 3: Mid-rapidity $R_{CP}$ ($|y| < 0.5$) in $d+Au$ $\sqrt{s_{NN}} = 200$ GeV collisions from default AMPT with (red circles) and without (black circles) final state interactions.

After including the final-state hadronic interactions and strong decays of resonances, the $R_{CP}$ of different particle species will change differently, as they have different masses and scattering cross sections. We show in Fig. 3 the comparisons of $R_{CP}$ with and without the final state rescatterings and resonance decays. For $\pi^-$ and $K^-$, the $R_{CP}$ decreases after including the final state interactions from intermediate to high $p_T$. And this suppression increases with $p_T$. Since most of the produced particles are pions at mid-rapidity, the scatterings are mainly the particle-pion interactions for $p \gg m_0$, where $m_0$ is the mass of corresponding particles. For $\pi^- \pi^+$ elastic collisions, the resonance peak centers at the position of $\pi^- \pi^+$ center-of-mass energy $\sqrt{s_{cm}}$ close to $\rho$ meson rest mass. Since most of the outgoing particles which probably scatter with each other are in the similar directions, the open angle between two scattering particles is small. In our studied $p_T$ and rapidity range, for one particle at low $p_T$, and another particle with higher energy, the calculated $\sqrt{s_{cm}}$ is closer to the resonance peak. As a result, this hadronic effect on $R_{CP}$ is enhanced with $p_T$ for pion. Similar argument is also valid for $k^- \pi^+$ scatterings. For heavier particles like antiproton, $\phi$ meson, $\Lambda$, the $R_{CP}$ increases at low $p_T$ according to their corresponding production channels or due to diffusions into mid-rapidity region, but changes slightly for $p_T > 3$ GeV/$c$. For even heavier particle, like $\Xi^-$, there is no obvious change of $R_{CP}$ due to the final state interactions. Here particle mass plays important roles in the hadronic rescatterings. It will determine the space-time configuration of formed hadrons [20].

Figure 4: (Color online) Mid-rapidity ($|y| < 0.5$) $R_{CP}$ in $d+Au$ $\sqrt{s_{NN}} = 200$ GeV collisions: (a) default AMPT with final state interactions; (b) string melting AMPT with final state interactions; (c) experimental data of $R_{CP}(p_{T})/R_{CP}(\pi^-)$ from STAR Collaboration; (d) the ratios of $R_{CP}(p)/R_{CP}(\pi^-)$ from STAR Collaboration, from default AMPT, from string melting AMPT, and from default AMPT without final state interactions.
According to above analysis, the final state hadronic rescatterings will lead to particle mass dependence of $R_{CP}$. In Fig. 4, we compare the data with model calculations. At intermediate $p_T$, the $R_{CP}$ of heavier particles like antiproton, $\phi$ meson, $\Lambda$, $\Xi$ will be larger than those of $\pi^-$ and $K^-$. The result is qualitatively consistent with experimental data [11], as shown in Fig. 4(c). At intermediate $p_T$, the $R_{CP}$ of antiproton is systematically larger than that of $\pi^-$. In Fig. 4(d), the ratio $R_{CP}(p)/R_{CP}(\pi^-)$ from the default AMPT model also agrees very well with experimental data. We note that the present calculation without including the possible quark intrinsic $p_T$ broadening at initial state can not reproduce the $p_T$ dependence of $R_{CP}$. This difference between data and model results may indicate that the initial state effect is important. The year 2008 data of RHIC with higher statistics will provide more precise measurements and test our predictions for other hadron species like $\phi$ meson, $\Lambda$, $\Xi$, etc.

For comparisons, the $R_{CP}$ from string melting AMPT with quark coalescence is also studied. We have shown in Fig. 2(c) that the excess of $\bar{s}$ quark over $s$ quark at mid-rapidity is partly due to associate production from initial multiple interactions. Combining this effect with the coalescence of partons, there are enhancements of corresponding hadrons at intermediate $p_T$. The $R_{CP}$ values for different particle species that contain different number of $\bar{s}$-quarks are shown in Fig. 4(b). Note, multi-strange hadrons are particularly interesting as they suffer much less hadronic interactions compared with non-strange hadrons. Therefore they are more sensitive to early stage dynamics. At intermediate $p_T$, there is an enhancement of $R_{CP}$ according to the number of $\bar{s}$ quarks, that is, $R_{CP}(\Lambda) < R_{CP}(\Xi^-) < R_{CP}(\Omega^-)$. Note that the values of $R_{CP}$ for strange particles (\Lambda, \Xi, and \Omega) are close to each other (not shown here) at the same transverse momentum region. If one assumes the validity of the coalescence approach, this observation shows that the measured $R_{CP}$ can, to some extent, reflect the density of quarks shortly before the freeze-out. However, from the coalescence calculation the $R_{CP}$ of antiproton is close to that of $\pi^-$ at intermediate $p_T$, which is not consistent with experimental data, as shown in Fig. 4(d).

4. Summary

In summary, we studied the mechanism of hadron formation and subsequent interactions in $d+Au$ collisions at $\sqrt{s} = 200$ GeV. In a multiphase transport model with Lund string fragmentation for hadronization and the subsequent hadronic rescatterings included, we find particle mass dependence of central-to-peripheral nuclear modification factor $R_{CP}$. Recent data on particle species dependence of $R_{CP}$ at mid-rapidity for $d+Au$ collisions at RHIC can be understood in terms of this final-state hadronic rescatterings. This shows the importance of final state hadronic interactions in $d+Au$ collisions, since none of the initial-state models would predict a species-dependent $R_{CP}$ at present. However, the calculations can not reproduce the $p_T$ dependence of $R_{CP}$ with only final state interactions, this indicates the initial state effects might be also important.

Issues associated with the initial condition such as gluon saturation and parton intrinsic $p_T$ broadening and so on were not addressed in this paper. The future more complete analysis should include these effects. In comparison, if the hadron is formed from quark coalescence, it is difficult to explain antiproton transverse momentum spectra and the particle species dependence of $R_{CP}$. On the other hand, the strangeness effect plays an important role. More precision data in the future will test the findings in this paper.

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References

[1] J. W. Cronin, H. J. Frisch, and M. J. Shochet, et al., Phys. Rev. D 11 (1975) 3105.
[2] D. Antreasyan, J. W. Cronin, and H. J. Frisch, et al., Phys. Rev. D 19 (1979) 764.
[3] STAR Collaboration, J. Adams, et al., Phys. Lett. B 66 (2005) 5 ; STAR Collaboration, J. Adams, et al., Phys. Lett. B 637 (2006) 161.
[4] PHENIX Collaboration, S. S. Adler, et al., Phys. Rev. C 74 (2006) 024904.
[5] STAR Collaboration, J. Adams, et al., Nucl. Phys. A 757 (2005) 102.
[6] M. Lev and B. Petersson, Z. Phys. C 21 (1983) 155.
[7] G. Papp, P. Lévai, and G. Fai, Phys. Rev. C 61 (1999) 021902(R).
[8] X. N. Wang, Phys. Rev. C 61 (2000) 064910.
[9] I. Vitev and M. Gyulassy, Phys. Rev. Lett. 89 (2002) 252301.
[10] B. Z. Kopeliovich, J. Nemchik, A. Schafer, and A. V. Tarasov, Phys. Rev. Lett. 88 (2002) 232303.
[11] A. Accardi and M. Gyulassy, Phys. Lett. B 586 (2004) 244.
[12] R. C. Hwa and C. B. Yang, Phys. Rev. Lett. 93 (2004) 082302; R. C. Hwa and C. B. Yang, Phys. Rev. C 70 (2004) 037901.
[13] X. N. Wang and M. Gyulassy, Phys. Rev. D 44 (1991) 3501.
[14] Z. Lin, C. M. Ko, B. Li, B. Zhang, and S. Pal, Phys. Rev. C 72 (2005) 064901, and references therein.
[15] Z. Lin and C. M. Ko, Phys. Rev. C 68 (2003) 054904.
[16] B. Zhang, Comput. Phys. Commun. 109 (1998) 193.
[17] STAR Collaboration, J. Adams, et al., Phys. Rev. C 70 (2004) 064907.
[18] STAR Collaboration, B. I. Abelev, et al., Phys. Rev. C 76 (2007) 064904.
[19] STAR Collaboration, B. I. Abelev, et al., Phys. Rev. C 79 (2009) 064903.
[20] K. Gallmeister, and T. Falter, Phys. Lett. B 630 (2005) 40.
[21] B. van Hecke, H. Sorge, and N. Xu, Phys. Rev. Lett. 81 (1998) 5764.
[22] L. V. Gribov, E. M. Levin, M. G. Ryskin, Phys. Rept. 100 (1983) 1.
[23] A. H. Mueller and J. Qiu, Nucl. Phys. B 268 (1986) 427.
[24] L. McLerran and R. Venugopalan, Phys. Rev. D 49 (1994) 2233; L. McLerran and R. Venugopalan, Phys. Rev. D 49 (1994) 3352.