Proton production in d+Au collisions and the Cronin effect

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Proton production in the intermediate p_T region in d+Au collisions is studied in the parton recombination model. The recombination of soft and shower partons is shown to be important in central collisions, but negligible in peripheral collisions. It is found that the large nuclear modification factor for proton production can be well reproduced by a calculation of the 3-quark recombination process.

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In a previous paper [1] we have shown that the Cronin effect [2] on pion production in d+Au collisions can be understood in terms of the recombination of the soft and shower partons without p_T broadening by multiple scattering in the initial state. In this paper we extend the consideration to proton production and show that the same effect can similarly be interpreted.

The Cronin effect can best be displayed by the nuclear modification factor $R_{CP}(p_T)$ that is the ratio of central-to-peripheral yields appropriately scaled by the average number of binary collisions $\langle N_{\text{Coll}}\rangle$. It is found in the PHENIX experiment that R_{CP}^p for proton reaches a value roughly 2 for $2<p_T<3$ GeV/c, even higher than that for pion at $\sim$1.4 [3]. Such a behavior of the enhancement effect is hard to interpret, if hadrons produced at intermediate p_T are the consequences of fragmentation of hard partons produced at higher p_T. Indeed, since there is no energy loss in d+Au collision, one would expect $R_{CP}\sim 1$ for both pion and proton on the grounds that fragmentation outside the cold medium should be independent of the impact parameter. Thus the observed $R_{CP}^{\pi,p}$ strongly suggests the dependence of the hadronization mechanism on the medium. In our view recombination is that mechanism, which, on the one hand, provides a way to describe fragmentation in terms of shower partons [4], and, on the other, can take into account the coalescence of soft and shower partons to form hadrons in the intermediate p_T range [5].

For the proton spectrum at low p_T, one should be careful about the mass effect. The low-p_T region is, however, not the main part of our work where the model has any predictive power. As in Refs. [1,5], we fit the data in that region and use our model to predict the hadronic spectra at intermediate and high p_T. We have found that for the purpose of data fitting at low p_T our 1D formulation of the recombination process is quite adequate when only the kinematical variables are suitably modified to account for the proton mass. Thus we start with the invariant inclusive distribution for proton formation at midrapidity in the recombination model [5,6]

$$p^0\frac{dN_p}{dp}=\int\frac{dp_1}{p_1}\frac{dp_2}{p_2}F(p_1,p_2,p_3)R_p(p_1,p_2,p_3,p), \qquad (1)$$

where all momentum variables p_i and p are transverse momenta, and p^0 denotes the energy of the proton. Since the parton masses are set to zero, we continue to use p_i for their energies. $F(p_1,p_2,p_3)$ is the joint distribution of u, u, and d quarks at p_1, p_2, and p_3, respectively. $R_p(p_1,p_2,p_3,p)$ is the recombination function for a proton with momentum p [5,7]

$$R_p(p_1,p_2,p_3,p)=g(y_1y_2)^{\alpha+1}y_3^{\gamma+1}\delta\left(\sum_i y_i-1\right), \qquad (2)$$

where $y_i=p_i/p$, $\alpha=1.75$, $\gamma=1.05$, and

$$g=[6B(\alpha+1,\alpha+\gamma+2)B(\alpha+1,\gamma+1)]^{-1}, \qquad (3)$$

$B(a,b)$ being the beta function. As always in the recombination model, the main issue is about the distribution of the quarks that recombine. Here, it is $F(p_1,p_2,p_3)$.

Following the same notation used in Ref. [5] for Au+Au collisions, we write schematically

$$F=\mathcal{TTT}+\mathcal{TTS}+\mathcal{TSS}+\mathcal{SSS}, \qquad (4)$$

where all the shower partons $\mathcal{S}$ are from one hard parton jet. Shower partons from different jets are ignored here for relativistic heavy-ion collider energies. $\mathcal{T}$ denotes thermal parton, even though in d+Au collisions the notion of thermal equilibrium may not be justified. To preserve the same notation as in Ref. [5], we continue to use $\mathcal{T}$ to signify the soft partons that are not associated with the shower components of a hard parton and are loosely referred to as thermal partons when convenient. The $\mathcal{SSS}$ term in Eq. (4), when convoluted with R_p in Eq. (1), gives rise to what is usually regarded as the fragmentation of a hard parton into a proton [4]. The $\mathcal{TTT}$ term comes entirely from the soft partons, while $\mathcal{TTS}$ and $\mathcal{TSS}$ accounts for the interplay between the thermal (or soft) and shower partons.

As in Refs. [1,5], we can calculate the distributions of the shower partons $\mathcal{S}$ from the QCD processes of producing hard partons and their induced shower partons. We cannot calculate the thermal component $\mathcal{T}$, which is deduced from fitting the low-p_T data. Thus what we can calculate that is new is only the effect of the $\mathcal{TTS}+\mathcal{TSS}$ terms at intermediate p_T, knowing that the $\mathcal{SSS}$ term dominates at very high p_T.

For $\mathcal{T}$ we use the same parametrization as before [1,5], and write

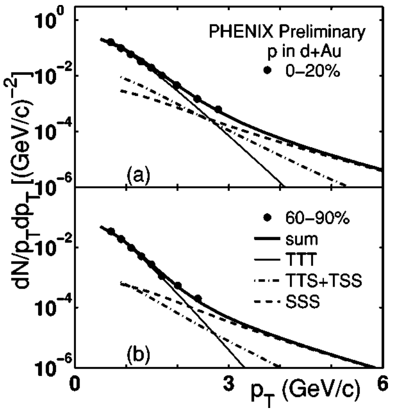

FIG. 1. (a) Proton transverse momentum distribution in $d+$Au collisions at 0–20% centrality. The preliminary data are from [8]. (b) Same as in (a), but for 60–90% centrality.

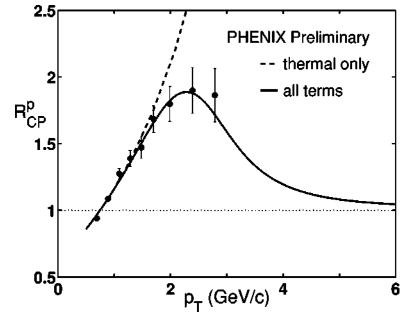

FIG. 2. Nuclear modification factor R^p_{CP} for proton production in $d+$Au collisions. The data are for 0–20% to 60–90% centralities [3]. The solid line is the result of our calculation when all contributions are taken into account, while the dashed line gives the ratio when only the thermal contributions are included.

$$\mathcal{T}(p_1) = p_1 \frac{dN_q^{\mathcal{T}}}{dp_1} = Cp_1 \exp(-p_1/T), \tag{5}$$

where T should be regarded as just an inverse slope. The thermal contribution to the proton spectrum arising from $\mathcal{TTT}$ recombination is then

$$\frac{dN_p^{\rm th}}{pdp} = \frac{C^3}{6}\frac{p^2}{p^0} e^{-p/T} \frac{B(\alpha+2,\gamma+2)B(\alpha+2,\alpha+\gamma+4)}{B(\alpha+1,\gamma+1)B(\alpha+1,\alpha+\gamma+2)}, \tag{6}$$

which differs from a similar formula in Ref. [5] by only the presence of p^0, instead of p. For the other three terms in Eq. (4) that involve $\mathcal{S}$, the contributions to the proton spectrum are the same as those in Ref. [5] except that each equation should be multiplied by the factor p/p^0 on the right-hand side and the factor ξ should be omitted. The latter is the suppression factor due to the mean energy loss in Au+Au collisions, and should be 1 in $d+$Au collisions. Also the hard parton distributions $f_i(k)$ in Ref. [5] should be changed to the corresponding ones for $d+$Au collisions, as given in Ref. [1]. What is to be emphasized is that there are no free parameters to adjust in those terms. The shower parton distributions are the main input, and they have previously been determined in Ref. [4].

We must now determine C and T by fitting the low-p_T data using Eq. (6) for both central and peripheral collisions. The data available are from PHENIX, given as figures online [8]. We fit them in the region $0.5 < p_T < 1.5$ GeV/c and the results are shown by the light solid lines in Figs. 1(a) and 1(b) for 0–20% and 60–90% centralities, respectively. The values determined are $C = 11.5\,(8.0)\,(\mathrm{GeV}/c)^{-1}$ and $T = 0.24\,(0.21)$ (GeV/c) for 0–20% (60–90%) centrality. The contributions from $\mathcal{TTS}+\mathcal{TSS}$ and $\mathcal{SSS}$ components are determined without free parameters, and are shown by the dashed and dash-dot lines in the same figures. The sum of all four components are shown by the thick solid lines. Evidently, they agree with the data very well.

We note that at 0–20% centrality the thermal-shower ($\mathcal{TTS}+\mathcal{TSS}$) contribution crosses over the fragmentation ($\mathcal{SSS}$) component at $p_T \approx 2.5$ GeV/c, roughly the same as in the case of pion production in $d+$Au collisions [1]. However, the thermal $\mathcal{TTT}$ contribution is roughly the same as each of the ($\mathcal{TTS}+\mathcal{TSS}$) and $\mathcal{SSS}$ contributions at the cross-over point, whereas for pion production the thermal $\mathcal{TT}$ contribution is much lower than $\mathcal{TS}$ and $\mathcal{SS}$ at the same point. Thus the thermal contribution to proton formation dominates over a wider range of p_T than that for pion. That is because of the C^3 dependence in Eq. (6), and is consistent with the findings in Refs. [9,10], where the recombination of thermal partons can account for the large p/π ratio up to $p_T \approx 3$–4 GeV/c Au+Au collisions. The same cannot be said about 60–90% centrality in $d+$Au collisions. The crossover between $\mathcal{TTS}+\mathcal{TSS}$ and $\mathcal{SSS}$ occurs at $p_T \approx 1$ GeV/c, where the distributions are far lower than the thermal contribution. Throughout all p_T in Fig. 1(b) the ($\mathcal{TTS}+\mathcal{TSS}$) component is negligible compared to ($\mathcal{TTT}+\mathcal{SSS}$). The reason is not so much the reduction of the soft component at low p_T in peripheral collisions (since C decreases by only 30%) as the significant reduction of the shower partons whose density is lowered by a factor of 4 on account of the much smaller value of $\langle N_{\rm coll}\rangle$ for 60–90% centrality. Thus for $p_T \sim 1$ GeV/c the ratio of $\mathcal{TTS}$ to $\mathcal{TTT}$ contributions is smaller for peripheral than for central collisions by a factor of 3. However, for $p_T > 3$ GeV/c that same ratio is bigger for the peripheral case because of the steeper exponential drop of the thermal component. Thus the phenomenon of crossover of the contributions from various components is the result of many unrelated factors. Since we have no way of calculating the thermal component from first principles, we can only fit the low-p_T data as best we can in the determination of the parameters C and T, and present our prediction for the behavior at higher p_T.

The fact that our calculated results agree well with the data for both 0–20% and 60–90% centralities implies that the ratio $R^p_{CP}(p_T)$, defined by

$$R^p_{CP}(p_T) = \frac{\langle N_{\rm Coll}\rangle_{60-90\,\%} dN_p/dp_T(0-20\,\%)}{\langle N_{\rm Coll}\rangle_{0-20\,\%} dN_p/dp_T(60-90\,\%)} \tag{7}$$

must also agree with the data. That agreement is shown explicitly in Fig. 2 by the solid line, where the data are from Ref. [3]. The calculated curve approaches 1 at high p_T, where the yields are dominated by the fragmentation of hard partons ($\mathcal{SSS}$), which is independent of the soft partons. The dashed line in Fig. 2 shows the contribution to R_{CP}^{p} from the thermal components only. The small difference in T for the two centralities results in an exponential growth in p_T as can be seen directly from Eq. (6). Thus the effect of thermal-shower recombination is the damping of that exponential increase in $R_{CP}^{p}(p_T)$, as shown by the solid line. Because of the ineffectiveness of the thermal-shower contribution at 60–90% centrality, that damping does not take place until p_T reaches near 2 GeV/c. By then R_{CP}^{p} is already greater than 1.7, which is higher than R_{CP}^{π}. Thus the origin of R_{CP}^{p} being greater than R_{CP}^{π} is mainly in the $\mathcal{TTT}$ recombination for proton being more sensitive to centrality than $\mathcal{TT}$ for pion. The role of shower partons is limited in that comparison.

It should be pointed out that our fitting procedure in the determination of C and T has not ignored R_{CP}^{p} as an outcome. Since Fig. 1 has logarithmic vertical scale, those data points can determine C and T only within narrow ranges. The data in Fig. 2 involve their ratios and are in linear scale. Thus the parameters can be more accurately determined by including Fig. 2 in the fit. Since the distributions of the soft partons at low p_T are not generated from first-principle calculations, we have taken the liberty to use all the data available to make the best determination of them. Our predictions are only for the behavior at p_T above the region that is dominated by the soft partons.

The values of C and T obtained here should be compared with those determined from the pion spectrum [1]. They are $C_\pi = 12\ (5.65)\ (\mathrm{GeV}/c)^{-1}$ and $T_\pi = 0.21\ (0.21)$ GeV/c for 0–20% (60–90%) centrality, where the subscripts π are added for distinction. Whereas there is no essential dependence of some of those parameters on whether the formed hadrons are pions or protons, i.e., $C_p \simeq C_\pi$ at 0–20% and $T_p = T_\pi$ at 60–90%, there exist some significant differences in others: $C_p = 8.0$, $C_\pi = 5.65$ at 60–90% and $T_p = 0.24$, $T_\pi = 0.21$ at 0–20%. The species dependence of those parameters reflects the general properties of the spectra, especially at $p_T < 1$ GeV/c. In Ref. [11] it is shown in Au+Au collisions that the low-p_T spectra can be fitted by exponential behavior in m_T with the inverse slope increasing linearly with hadronic mass at a rate that increases with centrality. It strongly suggests hydrodynamical expansion radially, which is well known to exist. It means that a significant portion of the hydrodynamical fluid is hadronic at very low p_T. Only the portion that remains partonic at p_T around 1 GeV/c and above are available for recombination with the shower partons. How much of this scenario is valid (and in what quantitative way) for d+Au collisions is not known. Since our hadronization model does not treat the hydrodynamical expansion phase, we can only take the thermal hadrons in the $0.5 < p_T < 1.5$ GeV/c range as observed, but not lower, to determine our parameters for the thermal partons $\mathcal{T}$. The species dependence of some of the C and T parameters is clearly a result of our inadequacy in subtracting out the already-formed hadrons from the medium at low p_T, since the thermal partons $\mathcal{T}$ should have no knowledge of what hadrons they are to form. Given our inability to treat very low p_T physics, we can only regard what we have done as a determination of the intermediate p_T behavior in the separate cases of specific hadrons without a way to enlighten the problem of overall species dependence at very low p_T in a broader scheme.

The important properties of hadron production in d+Au collisions that we have learned from this study is that the protons are formed by recombination at all p_T and that the underlying partons that give rise to their formation change smoothly from the soft component to the semihard shower partons that are created by the hard partons. The recombination formalism allows us to calculate the p_T distribution in the intermediate and higher p_T regions with good agreement with the data. The contribution from the recombination of soft and shower partons cannot be interpreted as a modification of the fragmentation function, since the hard partons in d+Au collisions are not significantly affected by the cold medium that they traverse. In this treatment the Cronin effect of the proton spectrum is not induced by transverse broadening due to initial scatterings, but is caused mainly by the centrality dependence of the soft partons that recombine. R_{CP}^{p} is higher than R_{CP}^{π} because the number of such recombining quarks is 3 instead of 2. Our approach cannot be viewed as being totally successful until the data for $p_T > 3$ GeV/c turn out to support our predictions in the higher p_T region.

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