Final-State Interaction as the Origin of the Cronin Effect

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Instead of adhering to the usual explanation of the Cronin effect in terms of the broadening of the parton transverse momentum in the initial state, we show that the enhancement of hadron production at moderate $p_T$ in $d+Au$ collisions is due to the recombination of soft and shower partons in the final state. Such a mechanism can readily explain the decrease of the Cronin effect with increasing rapidity. Furthermore, the effect should be larger for protons than for pions.

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The conventional explanation of the Cronin effect\cite{1}, i.e., the enhancement of hadron spectra at high $p_T$ in proton-nucleus ($pA$) collisions, is that it is due to multiple scattering of projectile partons by the target nucleus before the production of a minijet by a hard scattering \cite{2}. All models on the effect are based on the traditional approach to hadron production at high $p_T$, which is to follow a hard-scattered parton by a fragmentation of that parton. Since in that paradigm there is nothing more one can do with the final state, all models focus on the initial state, and they differ only in the way the broadening of the intrinsic traverse momentum is implemented. In this paper we consider a drastically different approach to the problem. We do not assume initial-state broadening, and treat the hadronization process in the final state by recombination \cite{2}. It will be shown that the Cronin effect can be satisfactorily explained at all centralities. In so doing we eliminate the necessity of putting in by hand successive transverse kicks of appreciable magnitude in the initial state.

The idea that final-state interaction may contribute to the Cronin effect is not new \cite{4,5}. However, no theoretical model has ever been proposed to demonstrate that the idea can be translated into quantitative accounting of the effect. Here we work in the specific framework of the recombination model and make concrete predictions. Although the model has long been used to treat hadronization in the fragmentation region, a number of groups have recently found that recombination is more important than fragmentation at small and moderate $p_T$ ($0 < p_T < 8$ GeV/$c$) at midrapidity in heavy-ion collisions at $\sqrt{s} = 200$ GeV \cite{6,5}. A central issue in the model has always been the determination of the appropriate distributions of partons that recombine, and it has been the major problem to tackle for the application of the model at low $p_T$ in hadron-hadron \cite{8} and proton-nucleus \cite{10} collisions. For high $p_T$ we have very recently determined the distributions of shower partons created by a hard parton \cite{11}, and then found that the recombination of thermal and shower partons is crucial in reproducing the observed spectra at moderate $p_T$ in Au+Au collisions \cite{12}. It is the thermal-shower recombination that also holds the key to the Cronin effect in $pA$ collisions. It is an effect due to the interaction between soft and hard partons during hadronization in the final state.

Unlike the case of Au+Au collisions at RHIC where the hydrodynamical expansion of a hot, dense system that is created leads to a large body of thermal partons, one does not expect such a scenario in $pA$ collisions. Nevertheless, there are soft partons that take the place of the thermal partons. They can participate in the formation of hadrons at moderate $p_T$. The number of such soft partons decreases with increasing impact parameter and rapidity, so our explanation of the Cronin effect naturally leads to a reduction of the effect at lower centrality and higher rapidity, in accordance to the observation at RHIC \cite{13}.

The inclusive distribution for the production of pions can be written in the recombination model, when mass effects are negligible, in the invariant form \cite{3,4}

$$ \frac{dN_\pi}{dp} = \int \frac{dp_1}{p_1} \frac{dp_2}{p_2} F_{q\bar{q}}(p_1,p_2) R_x(p_1,p_2,p), $$

(1)

where $F_{q\bar{q}}(p_1,p_2)$ is the joint distribution of a $q$ and $\bar{q}$ at $p_1$ and $p_2$, and $R_x(p_1,p_2,p)$ is the recombination function for forming a pion at $p$: $R_x(p_1,p_2,p) = (p_1p_2/p)\delta(p_1 + p_2 - p)$. Restricting $\vec{p}$ to the transverse plane, the distribution $dN_\pi/d^2pdy\big|_{y=0}$, averaged over all $\phi$, with $p_T$ denoted by $p$, is \cite{12}

$$ \frac{dN_\pi}{dp} = \int \frac{dp_1}{p_1} \int_0^p dp_2 F_{q\bar{q}}(p_1,p-p_1). $$

(2)

This equation is applicable to any of the $pp$, $pA$ and $AB$ collision types; only $F_{q\bar{q}}$ depends on the colliding hadron/nuclei. In general, $F_{q\bar{q}}$ has four contributing components represented schematically by

$$ F_{q\bar{q}} = \mathcal{T}T + \mathcal{T}S + (SS)_1 + (SS)_2, $$

(3)

where $\mathcal{T}$ denotes thermal distribution and $S$ shower distribution. ($SS)_1$ signifies two shower partons in the same hard-parton jet, while ($SS)_2$ stands for two shower partons from two nearby jets, in a notation more self-explanatory than the one used in \cite{12}. For simplicity, we shall at times abbreviate ($SS)_1$ by $SS$. 

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PHENIX preliminary data on p+p collisions at $\sqrt{s} = 200$ GeV and 0-20% centrality. The three components in the recombination model are $TT$, $TS$, and $SS$. We use the latter because they are for cold nucleus. We show in Fig. 1 the three components together with the sum of all three components. The integrals begin at a minimum $k_0$ below which the pQCD derivation of $f_i(k)$ is invalid. We set $k_0 = 3$ GeV/c. The curly brackets in Eq. (7) signify the symmetrization of the leading parton momentum fraction $f_i$. We have assumed in Eqs. (6) and (7) that the hard partons suffer no energy losses as they traverse the cold nucleus.

The hard parton distributions $f_i(k)$ depend on the parton distribution functions (PDF) in the proton and nuclear, and on the hard scattering cross sections. For d+Au collisions Fries has performed the convolution and put the inclusive distribution for the production of a hard parton $i$ at $y = 0$ and at 0-20% centrality in a generic form over a wide range of $k$

$$f_i(k) \equiv \frac{1}{\sigma_{in}} \left. \frac{d^2A_{d+Au}}{d^2k dy} \right|_{y=0} = K A_i \left(1 + \frac{k}{k_i}\right)^{-n_i}, \quad (8)$$

where $\sigma_{in} = 40.3$ mb has been used. The parameters $A_i$, $k_i$, and $n_i$ are given in Table I. Nuclear shadowing effects have been taken into account through the use of EKS98 PDF. The $K$ factor is due to higher order corrections in pQCD. We shall set it at 2.5, as in PHENIX preliminary 0-20%.

We calculate the three contributions $TT$, $TS$, and $SS$ to $F_{q\bar{q}}$ and then to $dN^{d+Au}_{\pi}/dp_T$ in Eq. (2). In the calculation there are two parameters: $C$ and $T$. They are adjusted to fit the low $p_T$ region of the data. The point of view we adopt is that the soft component specified by $C$ and $T$ is not the predictable part of our model. In treating them as free parameters we do not compromise the predictable part of our model, which is the magnitude of the contribution from the $TS$ component in the recombination compared to the other components: $TT$ at low $p_T$ and $SS$ at high $p_T$.

For d+Au collisions at RHIC, PHOBOS has published data on the $p_T$ spectra of charged particles, $(h^+ + h^-)/2$, over the range $0.25 < p_T < 6.0$ GeV/c for various centralities; however, the pseudorapidity range is $0.2 < \eta < 1.4$. PHENIX has preliminary data on $\pi^+$ production over a narrower $p_T$ range ($< 3$ GeV/c) but for $\eta = 0$ and $0 < \eta < 0.2$. We use the latter because they are for $\pi^+$ at $\eta = 0$. Although $p_T$ does not go above 3 GeV/c, the range is sufficient to determine $C$ and $T$, where the $TT$ contribution dominates, and where the deviation from the exponential behavior is just enough to reveal the $TS$ contribution. Our prediction is the spectra for $p_T > 1$ GeV/c.

![FIG. 1: Pion distribution in transverse momentum compared to the data on $\pi^+$ from PHENIX on d+Au collisions at $\sqrt{s} = 200$ GeV and 0-20% centrality. The three components in the recombination model are $TT$ (light solid line), $TS$ (dashed-dot line), and $SS$ (dashed line). Heavy solid line is the sum of all three components.](image-url)
data from [17] is good, considering the fact that only the exponential component is adjusted to fit. The noteworthy features of our result is that the thermal-shower ($TS$) and shower-shower ($SS$) components both become more important than the thermal-thermal ($TT$) component above $p_T = 2$ GeV/c and that $TS$ is greater than $SS$ for $p_T < 3$ GeV/c. The values of the parameters determined are (for 0-20% centrality)

$$C = 12 \text{ (GeV/c)}^{-1}, \quad T = 0.21 \text{ GeV/c}. \quad (9)$$

With the above value of $T$ we obtain from Eq. (5) for the soft component of the pions ($p_T \equiv p$)

$$\langle p_T \rangle = 2T = 0.42 \text{ GeV/c},$$
$$\langle p_T^2 \rangle = 6T^2 = 0.26 \text{ (GeV/c)^2}, \quad (10)$$

while Eq. (11) implies for the intrinsic transverse momentum $k_T$ of the partons ($k_T \equiv p_1$)

$$\langle k_T \rangle = T = 0.21 \text{ GeV/c},$$
$$\langle k_T^2 \rangle = 2T^2 = 0.09 \text{ (GeV/c)^2}. \quad (11)$$

While the numbers in Eq. (10) are conventional, the intrinsic width of the partons in Eq. (11) is very small compared to what is needed in the fragmentation models, generally $\langle k_T^2 \rangle > 1 \text{ (GeV/c)^2}$, even before broadening.

The shower-shower component in Fig. 1 is dominant for $p_T > 5$ GeV/c; it is the same as the usual contribution from parton fragmentation [11, 12]. The thermal-shower recombination is a unique feature of our model. It makes a dominant contribution in the $3 < p_T < 8$ GeV/c range in Au+Au collisions because of the large thermal component in the hot, dense system [12]. Here in the cold system only slightly excited, the values of $C$ and $T$ are lower, compared to 23.2 (GeV/c)$^{-1}$ and 0.317 GeV/c, respectively, in Au+Au collisions. Thus the $TS$ contribution is subdued, but still large enough not only to cause a substantial deviation of the spectrum from exponential behavior, but also to give rise to the Cronin effect without large intrinsic $\langle k_T^2 \rangle$ broadening, as we shall show. The ratio $TS/SS$ is independent of the normalization of $f_1(k)$ and hence unaffected by the value of $K$.

For other centralities of d+Au collisions we fix $T$ at the value determined for 0-20% centrality, i.e., $T = 0.21$ GeV/c, and use the values of $\langle N_{coll} \rangle$ given in [17] to rescale $f_1(k)$. We adjust the value of $C$ to fit the low $p_T$ normalization of the data [17]. The results we obtain for $dN_{coll}^{d+Au}/dp_T$ for all four centralities are shown in Fig. 2 and are in good agreement with the data. The main point to stress is that the soft parton $\langle k_T^2 \rangle$ width remains the same at 0.09 (GeV/c)$^2$, without being broadened by successive kicks before hard scattering. In our approach what are different at more peripheral collisions are the decreasing values of $C$, which are 11, 7.8, and 5.65 for 20-40%, 40-60% and 60-90%, respectively. The decrease of the density of the soft partons is a reasonable property of less central collisions, and can be generated in a Monte Carlo code; we merely take it from data, since it involves no new physics. The physics issue we want to emphasize is that the thermal-shower parton recombination is sensitive to the density of soft partons, and that component of the hadronization product affects the spectra in the moderately higher $p_T$ region, $1 < p_T < 4$ GeV/c.

There are inaccuracies in our calculation due to the use of the lowest order pQCD results for the parameters in Table 1, and the SPDs that inherit the uncertainties of the FFs [11]. However, their effects tend to cancel, if we take the ratio of the calculated spectra at different centralities. PHENIX has preliminary data on the central-to-peripheral nuclear modification factor [17]

$$R_{CP}(p_T) = \frac{\langle N_{coll} \rangle_{60-90\%} dN_{\pi}^{d+Au}/p_T dp_T}{\langle N_{coll} \rangle_{0-20\%} dN_{\pi}^{d+Au}/p_T dp_T (0-20\%)} \quad (12)$$

for $p_T < 6$ GeV/c. We can determine $R_{CP}(p_T)$ directly from the results of our calculation; it is shown in Fig. 3. Evidently, the theoretical curve agrees very well with the data [17]. The agreement clearly lends support to our view that the Cronin effect is due to the recombination of soft and shower partons in the final state without initial-state broadening.

The extension of our consideration to forward rapidities naturally explains the decrease of the Cronin effect observed in d+Au collisions [14], since the soft parton density decreases, as one moves from the central to the fragmentation region of the deuteron. We await the precise data in the low-$p_T$ region at higher $\eta$ in order to determine the $\eta$ dependence of $C$ in the soft component before calculating the pion spectra.

On the basis that the thermal-shower recombination is the component mainly responsible for the enhancement of $R_{CP}^\pi$ in the intermediate range of $p_T$ in Fig. 3, we can infer qualitatively here that for proton production the corresponding $R_{CP}^p$ should be even higher in the same region. The reason is that for three quarks to recombine in forming a proton, there are many more

![FIG. 2: Same as in Fig. 1 but for different centralities. The inverse slope $T$ is the same in all cases; $C$ is varied to fit the low-$p_T$ region.](image-url)
The data is from PHENIX for d+Au collisions at $\sqrt{s}=200$ GeV\textsuperscript{17}. The solid curve is the result of our calculation without adjustable parameter.

FIG. 3: Central-to-peripheral nuclear modification factor. Terms: $TTS + TSS + SSS + \cdots$\textsuperscript{12}, among which the $TTS$ contribution has a quadratic dependence on $C$, and is therefore more sensitive to centrality. Consequently, as the collisions become more central, $dN_c^{d+Au}/dydp_T$ should receive a larger boost from $TTS$ than does $dN_c^{d+Au}/dydp_T$ from $TS$, resulting in $R_{CP}$ being higher than $R_{CP}^p$. The data of PHENIX\textsuperscript{17} show that such a behavior has already been observed. That behavior is hard to interpret in a fragmentation model, since the broadening of the parton $k_T$ width in the initial state should be independent of what a hard parton fragments into. To determine $R_{CP}$ quantitatively in our approach, we need to take the proton mass effects into account, for which our scale invariant formalism is inadequate. That is a task to be done elsewhere.

In conclusion we have shown, both here and in\textsuperscript{12}, that the separation of final states into independent and noninteracting soft and hard components is invalid, except when $p_T$ is very large. At moderate $p_T$ where the Cronin effect is found, the interaction between the soft and shower partons is important. Since the density of soft partons depends on the number of participants even in d+Au collisions, the hadron spectra at moderate $p_T$ depend on centrality, when those soft partons recombine with the shower partons. Thus the enhancement of hadron production in more central collisions is a final-state effect, in contrast to the usual explanation in terms of initial-state fluctuations. The Cronin effect may now be regarded as another phenomenon in support of the recombination model besides the large $p/p$ ratio and scaling elliptical flow\textsuperscript{20}. Our result also gives credence to our assertion that shower partons form an essential component in the final state of a quark-gluon system produced in a heavy-ion collision before hadronization takes place, but whose existence has hitherto been overlooked.

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