Where is the jet quenching in \( Pb + Pb \) collisions at 158 AGeV?

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(April 20, 1998)

Because of the rapidly falling particle spectrum at large \( p_T \) from jet fragmentation at the CERN SPS energy, the high-\( p_T \) hadron distribution should be highly sensitive to parton energy loss inside a dense medium as predicted by recent perturbative QCD (pQCD) studies. A careful analysis of recent data from CERN SPS experiments via pQCD calculation shows little evidence of energy loss. This implies that either the life-time of the dense partonic matter is very short or one has to re-think about the problem of parton energy loss in dense matter. The hadronic matter does not seem to cause jet quenching in \( Pb + Pb \) collisions at the CERN SPS. High-\( p_T \) two particle correlation in the azimuthal angle is proposed to further clarify this issue.

Hard processes have been considered good probes of the dense matter which is produced in high-energy heavy-ion collisions and is expected to be in the form of deconfined quarks and gluons or a quark-gluon plasma (QGP) at high energy densities. These processes happen in the earliest stage of the collisions and therefore can probe the properties of the dense matter in its early form, whether a QGP or not. Furthermore, their production rates can be calculated with reasonable accuracy within pQCD parton model and has been tested extensively against vast experimental data in \( p+p \) and \( p+A \) collisions. These calculations incorporating minimum amount of normal nuclear effects (nuclear modification of parton distributions [2] and Cronin effect [3]) then provide a clean and reliable baseline against which one can extract signals of the dense matter. In this paper, we investigate what high-\( p_T \) particles from jet fragmentation tell us about the dense matter formed in \( Pb + Pb \) collisions at the CERN SPS.

Like other hard processes, large transverse momentum parton jets are produced in the early stage of high-energy heavy-ion collisions. They often have to travel through the dense matter produced in the collisions and finally hadronize into high-\( p_T \) particles in the central rapidity region. Recent theoretical studies [4] show that a fast parton will lose a significant amount of energy via induced pQCD radiation when it propagates through a dense partonic matter where the so-called Landau-Pomeranchuk-Migdal coherence effect becomes important. If this picture of parton energy loss can be applied to large transverse momentum parton jets in the central rapidity region of high-energy central \( A+A \) collisions, one should expect a leading parton to lose energy when it propagates through a long-lived dense matter. Since the radiated gluons will eventually become incoherent from the leading parton which will fragment into large-\( p_T \) hadrons, one then should expect a reduction of the leading hadron’s \( p_T \) or a suppression of the large-\( p_T \) particle spectrum [4][5]. At the CERN SPS energy, high-\( p_T \) jet or particle production \((p_T > 3 \text{ GeV}/c)\) is very rare and the power-law-like spectrum is very steep because of the limited phase space. It should be especially sensitive to any finite energy loss.

The single inclusive particle spectrum at large \( p_T \) in high-energy \( p+p \) or \( p+\bar{p} \) collisions can be calculated in a pQCD parton model with the information of parton distributions [14] and jet fragmentation functions [15] from deep-inelastic \( e+p \) and \( e^+e^- \) experiments. This is one of the early successes of the QCD parton model [1][2]. It was already pointed out that the initial transverse momentum before the hard scattering is very important to take into account at lower energies and can significantly increase the single inclusive differential cross section. The initial parton transverse momentum can be studied in detail via Drell-Yan (DY) [16][17], \( \gamma+\gamma \) and \( \gamma +\gamma \) production in \( p+p \) collisions.

To the lowest order of pQCD, the single inclusive particle production cross section can be written as [13],

\[
\frac{d\sigma^{pp}}{dyd^2p_T} = K \sum_{abcd} \int dx_a dx_b d^2k_aT d^2k_bT g_p(k_aT, Q^2) g_p(k_bT, Q^2) f_{a/p}(x_a, Q^2) f_{b/p}(x_b, Q^2) D^0_{h,c}(z_c, Q^2) \frac{d\sigma}{dz}(ab \rightarrow cd),
\]

where \( x_{a,b} \) are the fractional energies and \( k_{a,b} \) are the initial transverse momenta of the colliding partons. \( d\sigma/dt(ab \rightarrow cd) \) are the differential elementary parton-parton cross sections [13]. \( K \approx 2 \) is used to account for higher order corrections [20] and \( Q = P_{T,c} = p_T/z_c \). We will use MRSD-’ parameterization for the parton distributions \( f_{a/p}(x, Q^2) \) and BKK parameteriza-
tion for the jet fragmentation functions $D_{h/f}(z, Q^{2})$. We will use a Gaussian form for the initial-$k_T$ distribution $g_p(k_T, Q^{2}) = 1/(π(k_T^2)p)\exp(-k_T^2/(k_T^2)p)$ with a variance $\langle k_T^2/p \rangle = 1/(2 GeV^2/c^2) + 0.2Q^2\alpha_s(Q^2)$, where the $Q$-dependence accounts for initial $k_T$ from initial-state radiation (or higher order $2 \rightarrow 2 + n$ processes). The parameters are chosen to best fit the experimental data of high-$p_T$ particle spectra at all energies [21].

Because of the introduction of initial parton $k_T$, one of the Mandelstam variables for the elementary parton-parton scattering processes could vanish and cause the differential parton cross sections to diverge in certain phase space points. We use an effective parton mass $\mu = 0.8$ GeV to regulate the divergence as in the early studies [1]. The resultant spectrum is sensitive to the value of $\mu$ only at around $p_T \sim \mu$, where pQCD calculation is not reliable in any case.

Shown in Fig. 1 is an example of the calculated $\pi^{\pm}$ spectra in $p+p$ collisions at $E_{lab} = 200$ GeV. The agreement with experimental data is very good not only for the overall inclusive cross section but also for the isospin dependence as shown by the $p_T$-dependence of the $\pi^-/\pi^+$ ratio in the inserted figure. Similar analyses have been carried out at other energies up to Fermilab Tevatron [21]. The initial $k_T$ is less important and becomes almost negligible for the single inclusive parton spectra at these collider energies.

In $p+A$ collisions, there are two known nuclear effects: nucleon modification of the parton distributions (EMC effect) [3] and nuclear enhancement of the large-$p_T$ hadron spectra (Cronin effect) [1]. Both are caused by multiple initial scattering. We assume that the parton distributions per nucleon inside a nucleus at impact parameter $b$,

$$f_{a/A}(x, Q^2, b) = S_{a/A}(x, b) \left[ \frac{Z}{A} f_{a/p}(x, Q^2) + (1 - \frac{Z}{A}) f_{a/n}(x, Q^2) \right], \quad (2)$$

is factorizable into the parton distributions inside a normal nucleon and the nuclear modification factor, $S_{a/A}(x, b)$, for which we use the HIJING parameterization [22]. This should be adequate at the CERN SPS energy where the dominant process at large $p_T$ is quark-quark scattering.

One can explain the Cronin effect within a multiple parton scattering model [23], in which the cancellation by the absorptive processes forces the nuclear enhancement to disappear at large $p_T$ like $1/p_T^n$ and in the meantime causes a slight suppression of hadron spectra at small $p_T$ so that the integrated spectra do not change much. This allows us to take into account the effect of multiple scattering via a broadening of the initial transverse momentum,

$$\langle k_T^2 \rangle_A(b) = \langle k_T^2 \rangle_p + |\nu(b) - 1| A \Delta^2, \quad (3)$$

where $\nu(b) = \sigma_{pp} t_A(b)$ is the average number of scattering the parton’s parent nucleon has suffered and $t_A(b)$ is the nuclear thickness function normalized to $\int d^2 b \sigma_{pp} t_A(b) = A$. Since the Gaussian distribution is not a good approximation for the $k_T$-kick during the initial multiple scattering, we found that we have to use a scale-dependent value, $\Delta^2 = 0.225 \ln^2(Q/GeV)/(1 + \ln(Q/GeV)) GeV^2/c^2$, to best describe the available data from $p + A$ collisions [21] which allow about 10–20% uncertainty in the calculated spectra. For $Q = 2 - 3$ GeV, $\Delta^2 = 0.064 \sim 0.129 GeV^2/c^2$, which is consistent with the analyses of $p_T$ broadening for $J/\Psi$ production in $p + A$ [22].

Taking into account these nuclear effects which already exist in $p + A$ collisions, the single inclusive particle spectra in $A + A$ collisions can be estimated as

$$\frac{d\sigma_{AA}}{dy d^2p_T} = K \sum_{abcd} \int d^2b \int d^2r t_A(r) t_A(|b - r|) \int dx_a dx_b d^2k_a d^2k_b g_A(k_a T, Q^2, r) g_A(k_b T, Q^2, |b - r|) f_{a/A}(x_a, Q^2, r) f_{b/A}(x_b, Q^2, |b - r|) D_{h/f}(z_c, Q^2) \frac{d\sigma}{dt}(ab \rightarrow cd). \quad (4)$$

The initial-$k_T$ distribution $g_A(k_T, Q^2, b)$ is similar to that of a proton in Eq. (1) with a broadened width given by Eq. (3) which now depends on the impact-parameter $b$.

For central $A + A$ collisions, we limit the integration over the impact parameter to $b_{max}$. Using the geometrical cross section of a hard-sphere nucleus, we determine
\[ b_{\text{max}} \text{ by matching } b_{\text{max}}^2 / 4\pi R_A^2 (R_A \approx 1.12 A^{1/3} \text{ fm}) \text{ to the} \]
\[ \text{fractional cross section of the triggered central events in experiments. In Eq. 3, we actually use the Wood-Saxon distribution to calculate the thickness function } t_A(b). \]

Shown in Fig. 2 are the calculated single-inclusive spectra for \( \pi^0 \) in central \( S + S (E_{\text{lab}} = 200 \text{ GeV}) \) and \( Pb + Pb \) \( (E_{\text{lab}} = 158 \text{ GeV}) \) collisions with (solid) and without (dashed) nuclear \( k_T \)-broadening as compared to WA80 \[27\] and WA98 \[28\] data. Besides small effects of the nuclear modification of the parton distributions on the spectra at these energies, the dashed lines are simply the spectra in \( p + p \) collisions multiplied by the nuclear geometrical factor. It is clear that one has to include the \( k_T \)-broadening due to the initial multiple scattering in order to describe the data. This is also consistent with the analysis by WA80 \[27\].

![Diagram](image-url)

**FIG. 2.** Single-inclusive \( \pi^0 \) spectra in central \( S + S \) at \( E_{\text{lab}} = 200 \text{ GeV} \) and \( Pb + Pb \) collisions at \( E_{\text{lab}} = 158 \text{ GeV} \). The solid lines are pQCD calculations with initial-\( k_T \) broadening and dashed lines are without. The \( S + S \) data are from WA80 \[27\] and \( Pb + Pb \) data are from WA98 \[28\]. The dot-dashed line is obtained from the solid line for \( Pb + Pb \) by shifting \( p_T \) by 0.2 GeV/c.

One can conclude from this analysis that the factorized pQCD parton model seems to work well for large-\( p_T \) hadron production in \( A + A \) collisions. But one can also immediately realize that there is no evidence of parton energy loss as predicted by previous theoretical studies \[4–7\]. If there is parton energy loss and the radiated gluons become incoherent from the leading parton, the effective fragmentation functions should be modified such that the leading high-\( p_T \) particles should be suppressed as compared to \( p + p \) and \( p + A \) collisions \[8–10\]. At \( y = 0 \), parton energy loss can be directly translated into \( p_T \) reduction for the leading hadrons. To estimate the experimental constraints on parton energy loss, one can simply shift the \( p_T \) values of the solid line for \( Pb + Pb \) in Fig. 2 by 0.2 GeV/c (dot-dashed line). Assuming 20\% uncertainty of the calculated spectrum, one can quickly exclude a total energy loss \( \Delta E < 0.1 \text{ GeV} \). With the transverse size of a \( Pb \) nucleus, this corresponds to an energy loss \( dE/dx < 0.02 \text{ GeV/fm.} \) Detailed model calculations will give a more stringent limit \[24\]. This is in direct contradiction with the current theoretical studies of parton energy loss in dense matter and calls into question current models of energy loss. It also implies that there is not a dense partonic matter which exists long enough to cause parton energy loss.

Most of the recent theoretical studies \[4–7\] of energy loss are based on pQCD calculation for a single fast parton propagating through a large dense medium. If we assume that it is valid for a parton propagating through a deconfined medium, the absence of parton energy loss in the experimental data on high-\( p_T \) particle spectra implies that either there is no such deconfined partonic matter being formed or it only lived for a very short period of time. Using the measured \( dE_T/d\eta \approx 405 \text{ GeV} \) \[29\] in the central rapidity region of most central \( Pb + Pb \) collisions \%(2 of the total inelastic cross section) one can estimate the initial energy density at \( \tau_0 = 1 \text{ fm/c} \) to be about \( \epsilon_0 = dE_T/d\eta/(\pi \tau_0 R_A^2) \approx 2.9 \text{ GeV/fm}^3 \). This is an optimistic estimate assuming that the formation time of the dense matter is about \( 1 \text{ fm/c} \). Because of longitudinal expansion, the energy density will decrease like \( \epsilon/\epsilon_0 = (\tau_0/\tau)^\alpha \). The value of \( \alpha \) could range from 1 for free-streaming to 4/3 for hydro-expansion of an ideal gas of massless particles. Assuming a critical energy density of \( \epsilon_c \approx 1 \text{ GeV/fm}^3 \), the system can only live above this critical density for about \( 2 \sim 2.9 \text{ fm/c} \). Equilibrating processes and transverse expansion certainly will reduce this lifetime even further. During such a short time, a highly virtual parton has small interaction cross section before its virtually decreases through pQCD evolution. Therefore, a produced large \( p_T \) parton will not have much time to lose its energy before the dense matter drops below the critical density. The recent theoretical studies \[4–7\] are not applicable to such a short-lived system. Nevertheless, this analysis at least tells us that the lifetime of the dense partonic matter must be short if it is ever formed in \( Pb + Pb \) collisions at 158 AGeV. Otherwise, it is difficult to reconcile the absence of parton energy loss with the strong parton interaction which drives the equilibration and maintains a long life-time of the initial parton system.

One definite conclusion one can draw from this analysis is that the hadronic matter in the later stage of heavy-ion collisions does not seem to cause parton energy loss or jet quenching at the CERN SPS. This will make jet quenching an even better probe of long-lived initial partonic matter since it will not be affected by the hadronic phase of the matter. Because of its long formation time \( (\tau_f \sim 20 \text{ fm/c} \) for a pion with \( p_T \sim 3 \)
GeV/c), a high-$p_T$ pion is only formed either after freeze-out or in a very dilute hadronic matter. Otherwise, inelastic scattering with other soft pions can also cause the suppression of high-$p_T$ particle spectra or apparent jet quenching. What is traveling through the hadronic matter is thus a fragmenting parton whose interaction with a hadronic matter might be non-perturbative in nature. The pQCD estimate of parton energy loss is then not applicable here even though it might be adequate for a parton propagating in a hot QGP. The fact that a fragmenting parton does not lose much energy in hadronic matter might be related to the absence of parton energy loss to the quarks and anti-quarks prior to DY hard processes in $p + A$ and $A + A$ collisions.

The initial energy density at RHIC is expected to be higher than at SPS. If one observes significant suppression of large-$p_T$ hadrons at RHIC as was predicted \cite{8,10}, it clearly reveals an initial condition dramatically different from the CERN SPS.

The observed high-$p_T$ pion spectra in central $Pb + Pb$ collisions cannot be due to collective hydrodynamic flow, since there will always be high-$p_T$ partons produced in the coronal region of the two overlapped nuclei where jet propagation and fragmentation will not be influenced by the dense matter. To verify that these spectra are from jet production and fragmentation rather than from hydrodynamic flow, one can measure the azimuthal particle correlation (selecting particles above a certain $p_T$) relative to a triggered high-$p_T$ particle as was proposed in Ref. \cite{16}. One should see a double-peak structure characteristic of a jet profile. One can use this method at even moderate $p_T$ (where there are still not many particles per event) to determine the contribution from semi-hard processes and the $p_T$ range for which use of a thermal fire-ball model is justified. Otherwise, the extracted temperature and radial flow velocity can be misleading.

**ACKNOWLEDGMENTS**

The author would like to thank M. Gyulassy, U. Heinz, B. Jacak and B. Müller for intense discussions on the implications of the absence of energy loss at the CERN SPS. He would also like to thank T. Peitzmann for communication regarding WA80 and WA98 data. This work was supported by DOE under Contract No. DE-AC03-76SF00098. The author wishes to thank the Institute for Nuclear Theory for kind hospitality during his stay when this work was written.