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Journal

Nuclear physics A, 527

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Publication Date

1990-09-01

Lawrence Berkeley Laboratory

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Submitted to Nuclear Physics A

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September 1990

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JET QUENCHING AS A PROBE OF DENSE MATTER

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This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

JET QUENCHING AS A PROBE OF DENSE MATTER

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We estimate the quenching of QCD hard jets in nuclear collisions at RHIC with particular emphasis on the consequences of a possible decrease in dE/dx at the critical point of the deconfinement phase transition.

As was first pointed out by Bjorken¹ in 1983, the attenuation of QCD hard jets in ultrarelativistic nuclear collisions is sensitive to the energy loss mechanism, dE/dx , of a high energy parton traversing the dense excited matter produced in these reactions. Hard jets can serve as "external" probes, as they are produced at times much earlier than the transient dense matter, and their production rates can be calculated via perturbative QCD² (up to a slowly varying correction factor $K \sim 2$). In what follows, we estimate the quenching of hard jets at RHIC energies and study its sensitivity to a possible decrease in dE/dx associated with the phase transition from hadronic matter to the quark-gluon plasma.

In Ref.1, the energy loss per unit distance of a parton of energy E due to elastic collisions with thermal partons in a perturbative quark-gluon plasma at temperature T was calculated,

$$(dE/dx)_c \approx 6C_i \alpha_s^2 T^2 \log(4ET/M^2) e^{-M/T} (1 + M/T), \quad (1)$$

where M is an infrared cutoff on the order of the Debye mass, α_s the strong coupling and C_i a color factor ($C_i = 1$ for quarks and antiquarks, and $C_i = 9/4$ for gluons). For $E \sim 20$ GeV and the values used in ref.1, $T \sim 0.25$ GeV, $\alpha_s \sim 0.2$ and $M = 0.5$ GeV, eq.(1) yields $(dE/dx)_c \sim 0.1$ GeV/fm, a value small compared to the string tension $\kappa \simeq 1$ GeV/fm characteristic for the confined hadronic phase. In principle, the coupling α_s could increase strongly as the critical temperature T_c of the deconfinement phase transition is approached. However, lattice data^{3,4} seem to indicate⁵ that at least the static coupling could remain quite small near and even at T_c . We have estimated⁵ the energy loss due to bremsstrahlung, $(dE/dx)_{br}$, and found that for an abelian plasma, $(dE/dx)_{br}$ is strongly suppressed due to the Landau-Pomeranchuk⁶ effect. Dimensional arguments suggest⁵ that in the nonabelian case $(dE/dx)_{br}$ should be at most of the same order as $(dE/dx)_c$.

For the hadronic phase, $(dE/dx)_H$ at temperature $T = 0$ can be studied by analysing the nuclear attenuation of secondary hadrons produced in inelastic lepton-nucleus reactions. In a recent analysis⁷ of data⁸ corresponding to jet energies $E \sim 10$ GeV, we found that the observed strong, uniform suppression of secondaries down to energies of 1 GeV cannot be explained in terms of final state cascading alone, not even in the limit of zero formation length. As an example for an additional energy loss mechanism we considered a string flip scenario where the leading quark

of the jet can suffer color exchange interactions with partons of the target nucleons, thus splicing the initial string configuration into many short segments and a leading string of reduced energy $\sim E - \kappa R_A$, where R_A is the nuclear radius. We found that $(dE/dx)_h = \kappa \gtrsim 1$ GeV/fm is required in order to account for the suppression of low energy hadrons.

Thus, it is conceivable that, as a consequence of the change in the energy loss mechanism at the phase transition point, dE/dx decreases as a function of temperature in the vicinity of the critical temperature T_c ; there may be a discontinuity in dE/dx if the phase transition is first order. In order to study the implications for the A -dependence of jet quenching in ultrarelativistic nuclear collisions, we have to determine the time variation of the energy loss mechanism, $ddE(\tau)/dx$. We apply scaling hydrodynamics with Bjorken initial conditions⁹, and use a bag model equation of state⁹ for the description of the deconfined phase. Let ϵ_H and ϵ_Q be the energy densities at the transition points from the confined hadronic phase to the mixed phase, and from the mixed to the pure plasma phase, respectively, and B the bag constant. If dE/dx is taken to be constant in the hadronic phase, $dE(\tau)/dx$ is completely determined⁵ if one specifies the values of ϵ_H , ϵ_Q , B and the initial proper time τ_0 . As it turns out that the excited matter spends most of its time in the mixed phase, in what follows we shall take $(dE(\tau)/dx)_H \equiv \kappa_H$ and $(dE(\tau)/dx)_Q \equiv \kappa_Q$ in the confined and in the pure deconfined component, respectively.

For a central $A+A$ collision, we shall consider the attenuation of back-to-back jets at $y_1 = y_2 = 0$ in the cm frame. Initially their transverse momenta are $p_{1\perp} = p_{2\perp} = p_\perp$. In passing through the excited matter, a jet parton i loses an amount of energy

$$\Delta E_i(\tau, \phi) \approx C_i \int_0^{\tau_f(r, \phi)} d\tau dE(\tau)/dx, \quad (2)$$

where $r = |\vec{r}|$ is its initial transverse radius and ϕ is the jet angle relative to $\vec{r}$ in the plane perpendicular to the beam axis; for a solid cylinder geometry, $\tau_f(r, \phi) = (R_A^2 - r^2 \sin^2 \phi)^{1/2} - r \cos \phi$. In order to minimize the washing out of the quenching effect due to fluctuations in the initial coordinates, we shall study the distribution in the *summed* energies of correlated back-to-back jets, $E_{tot} = 2p_\perp - (\Delta E_1 + \Delta E_2)$. The attenuation rate is then given by

$$R_{AA}(E_{tot}) = \frac{1}{\sigma_0(E_{tot})} \int_0^{R_A^2} \frac{2dr^2}{R_A^4} (R_A^2 - r^2) \int_0^{2\pi} \frac{d\phi}{2\pi} \sum_{i,j} \sigma_{ij}(\frac{1}{2}(E_{tot} + \Delta E_i + \Delta E_j)), \quad (3)$$

where we have averaged over the direction and initial coordinates of the dijet. $\sigma_{ij}(p_\perp)$ is the production cross section for a back-to-back dijet of parton species i and j at $y_1 = y_2 = 0$ in the CM frame, calculated as in Ref.10 with $K = 2.5$, and $\sigma_0(E) = \sum_{i,j} \sigma_{ij}(E/2)$. Fig.1 shows the quenching rate for a dijet of total energy $E_{tot} = 30$ GeV as a function of A at RHIC energies, $\sqrt{s} = 200$ AGeV. At this energy, in reactions like $Au + Au$ or $U + U$, dijets of $E_{tot} = 30$ GeV are produced at measurable rates of $\sim 10^{-3}$ per central collision. For the A and s dependence of the initial energy density ϵ_0 , we have taken the results of Ref.10 which contain both a soft and a semi-hard component, with $\tau_0 = 1$ fm, and we have used the parameters $T_c = 190$ MeV, $\epsilon_Q = 2.5$ GeV/fm³, $\epsilon_H = 0.5$ GeV/fm³, and $B = 0.5$ GeV/fm³ in the bag model equation of state.

One can see that the quenching effect is quite strong: production rates are suppressed by about an order of magnitude. Moreover, the A dependence is sensitive to the values of dE/dx for

FIGURE 1

Reduction factor for dijets of energy $p_{\perp 1} + p_{\perp 2} = 30 \text{ GeV}$ as a function of A

the confined hadronic and for the deconfined plasma phase, i.e., to the change in the energy loss mechanism. For $\kappa_Q/\kappa_H = 0.2$, one observes a small discontinuity in the slope of R_{AA} near $A \approx 40$, which for our choice of parameters is the critical A beyond which time evolution of the hot and dense matter starts in the pure plasma phase. We note that the discontinuity in the slope decreases as κ_Q/κ_H increases, while it is enhanced if the latent heat, $\epsilon_Q - \epsilon_H$, is reduced at fixed ϵ_Q . In any case, it would require high precision measurements to detect it, provided it is not washed out by nuclear surface effects.

To summarize: we have estimated the quenching of QCD hard jets in ultrarelativistic nuclear collisions at RHIC energies. The effect is strong, leading to attenuation of production rates by about an order of magnitude, and it is sensitive to the energy loss mechanism, dE/dx , in the transient dense matter. We have argued that a decrease in dE/dx may occur at the critical temperature, and that in this case the relative reduction in jet quenching could provide a signal for the deconfinement phase transition. A problem we have not mentioned so far is the huge mini-jet background expected in nuclear collisions at RHIC, which may make a detection of hard jets by calorimetry extremely difficult. A recently created event generator¹¹ of nucleus nucleus collisions which includes hard, semi-hard and soft interactions as well as a simple jet quenching algorithm, may help to establish kinematic regions and observables most sensitive to the jet quenching effect.

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