Jet-medium interaction and heavy quark energy loss

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In relativistic heavy ion collisions, the interaction between the jet and the quark-gluon medium has an analogy of high energy hadronic scattering. Pionization provides the key for understanding the experimental results of the energy loss of heavy quark, and several other 'puzzles'. The space-time picture of this interaction is discussed. Experimental tests are suggested.

By relativistic heavy ion (A-A) collisions, it is expected to produce de-confined quark-gluon matter (QGM, here refers to any possible state reached after the collision, not necessarily the de-confined or thermalized one), which is a new and special arena for Quantum Chromodynamics (QCD). These matter states present the most dense medium which human being has been able to produce. Investigation on results of their coupling with gravity hence geometry can provide copious information for cosmology study [1].

One of the genius ways to probe these states (e.g., their density) of the medium after the violent A-A collision is 'jet tomography', which relies on the mechanisms of the interactions between the hard parton (with large transverse momentum p_T) created in the initial collisions and the QGM. A lot of phenomena predicted by such an idea have been observed at the relativistic heavy ion collider (RHIC). The list of references on early pioneering works setting up this idea, as well as to-date formulations and experiments can be found in Ref. [2].

Until now, it is adopted that the medium-induced coherent bremsstrahlung from the hard parton is the dominant mechanism of its energy loss, which, physically, is a straightforward extrapolation of the 'parton shower' from vacuum to medium. In consequence, the dead cone effect for the massive quark (charm or bottom, referred as c or b in the following) case is a typical property [3]. However, experiments [4] on p_T spectra of non-photonic leptons from heavy quark (without distinguishing c or b) decays indicate that the energy loss of the heavy quarks is almost the same as that of the light ones. Recent results of jet in A-A collisions [5] showes that the jet is significantly 'quenched', but contrary to expectations, no apparent modification of the associate fragmentation function (FF) relative to hadron-hadron (h-h) collision is observed.

In this paper we revisit 'pionization' [6,7] common to all high energy hadronic collisions, and apply this property to the 'effective collision' between the hard jet and QGM. The *stochastic* (rather than collinear) nature of the emission angle of the pionization products is helpful to understand why the dead cone affects little and why the FF associate with jet in A-A collision is similar as that in h-h collisions. And there are more puzzles can be understood based on this picture (see following). The corresponding process for pionization in the Quantum Electrodynamics (QED) case is (fermion) pair production [6,7]. Electromagnetic energy loss of electron or muon in medium from electron-positron pair production exceeds that from photon bremsstrahlung at enough high energies (see, e.g., [8,9]).

Pionization products correspond to the particles which constitute the 'rapidity plateau' in high energy hadronic scattering [6,7]. They may be important component of the QGM in A-A collision but are irrelevant to the high p_T partons created in the rare hard interactions, which is employed as the hard probe. Here we discuss the pionization in the *effective high energy jet-QGM scattering*, which mimics the interactions between the hard probe parton and the QGM. The physical picture hence should be first clarified and established now.

With the naïve parton picture, it is easy to find that in any scatterings, if no QGM produced and residual around the overlap region of the two colliding objects, a hard parton created within the space-time scale $1/Q$ in the time of overlap, will never 'meet' anything more than the vacuum in the following time ($t > 1/Q$, if choosing t=0 for the time when the overlap begins). So its following radiation is the hard interaction induced bremsstrahlung. The dominant phase space is collinear and soft, resulting to the 'Sodukov double log' ($LogELogp_T$, with $E \sim p_T \sim Q$)[10]. The most simple example is the $e^+e^- \to q\bar{q}$. Each moves apart back to back, radiations induced by the hard process (say, quark pair hit by the virtual photon or Z^0) develop dominantly soft and collinear. In the Breit frame to observe deeply inelastic scattering, one find the very similar picture. That is, the parton (x is not very large) hit by the virtual photon turns back in the space-time scale $1/Q$, after this interval, the remnant of the hadron (or nuclear) has passed this region (taking into account the Lorentz contraction). So these two issues move apart back to back, contrary to some belief that the hard parton goes through the remnant as passing via 'cold quark gluon matter'. The radiation induced by this hit develops just as the case of e^+e^-. Extra 'initial state radiation' has the similar property. A very simplified example (but containing all the main elements) treated in quantum electrodynamics can be found in Peskin and Schroeder's quantum field theory text book. This analysis can be applied to hadronic interactions. All these suppose that, during the overlap of the two highly Lorentz contracted colliding issues, hard interaction happens, all the other 'underlying reactions' will not change the property of the vacuum, so the hard parton in the following evolution travels in vacuum, leaving apart from all the others from the hadron(s). However, the hard probe issue is just contrary, in which some QGM produced by underlying interactions during the overlap, develops and expands around the overlap region. In this case, the hard parton will collide with gradient(s) of the QGM in subsequential traveling. So, if the behaviour of energy loss in A-A is just the similar as in other processes, e.g., obvious dead cone effects observed, this could mean no QGM produced. Very the contrary case that dead cone effects not observed, make it possible to deduce the belief that the vacuum is changed (whether thermalized or not is irrelevant).

Jet is a bundle of collimated, on shell particles, with the invariant mass M of them (as whole) much smaller than the energy/virtuality Q at which the jet (rigorously to say, the hard parton initializing the jet) is created. We use E, p_T to denote its energy and transverse momentum, respectively, with $E \sim p_T \sim Q$ in our discussions. This energetic hard parton evolutes from the space-time scale $\sim 1/p_T$ to $\sim 1/M$ ($M << p_T$) by gluon radiation, and the jet is preliminarily shaped, defined by various infrared safe jet algorithms at partonic level (referred as 'preliminary jet' in the following). Because $1/M << 1fm$, just the asymptotically free region of QCD, any extra interaction or radiation via momentum transfer $\sim> M$ will lead to extra suppression by (small) α_s and (large) denominator of the propagator (all $\sim> M$). So the evolution during $1/p_T$ to $1/M$ (hence the preliminary jet) is hardly different whether it is created in h-h, A-A, e^+-e^-, or other collisions. However, the subsequent evolutions to larger space-time scale will recognize the 'environment'. The uniqueness of 'central' A-A collision is the existence of the QGM rather than the vacuum in other more 'simple' scatterings. Because $M << p_T \sim E$, *the jet as a whole can be taken as an energetic composite particle with energy E and mass M hitting and passing through the QGM as target (Such is the jet tomography),* with the space-time picture discussed in last paragraph. Each member (parton) of the jet, as the rôle of constituent, will interact with the QGM. So *the jet interacting with the QGM is quite in common as the high energy hadronic* *or nuclear scatterings such as a proton or nucleus hitting a target.* Based on such a physical picture, without referring to any of the microscopic details of the QGM and the energy and p_T distribution of the preliminary jet, but employing the properties common to any hadronic collisions drawn from experimental facts (e.g., pionization and limiting fragmentation), one can qualitatively explain the above mentioned experimental 'paradoxes' at RHIC[11]. This is desirable since QGM is 'uncharted', while the distribution of the preliminary jet is not well predictable if factorization is broken, at the case that the multiplicity is triggered hence the unitarity of the summation of soft interactions is violated.

Further discussions to be found in [11]. The experimental condition for jet tomography helps to understand why pionization dominant. The hard trigger in A-A only make sure a hard jet produced (hardly soft parton becomes hard by absorbing energy from medium, this even contradicting to the 2nd law of thermodynamics). But the subsequential interactions with the medium are not controllable. So the total inelastic cross section rather than the *rare* hard part of the effective jet-medium scattering is relevant.

The pionization products are characteristic of the phase space dominated by $k^+ \sim k^-$, i.e., modest rapidity, in center of mass frame. The collinear approximation for the phase space, $k^0 >> k_T$ ($k^+ >> k^-$ or $k^- >> k^+$), only valid for the fragmentation (bremsstrahlung), misses almost all the pionization products. For incorporating pionization, one must take into account the "full" phase space (all the rapidity region). In which for fixed energy, the angular distribution is random. Systematic calculations and arguments to all orders, with the gluon propagators reggeized, result in the extended eikonal formula (see [6] and refs. therein, which also give brief accounts for the relation with the "pomeron"), which gives the S-matrix of the scattering process in impact parameter space via the eikonal operator. The extended eikonal formula implies a physical picture of multi-production of high energy scattering. It is a stochastic process in which quanta are created and annihilated in a random way [6]. Though the transverse degrees of freedom distribute according to the specific dynamics and the structure of colliding issues, the longitudinal distribution is just the rapidity plateau, with width proportional to $\ln s$, and s the center of mass energy squared of the scattering. This is the microscopic basis of our extrapolating the property of pionization to the effective jet-QGM collision and indicates the increase of the relative rate of the pionization energy loss with the jet energy due to the logarithmically increasing rapidity plateau width. The pionization energy loss of the preliminary jet can be estimated to be

$$< \Delta E >= \int_{y_{min}}^{y_{max}} dy d^2 k_T \Big(\frac{d\sigma}{dy d^2 k_T}\Big) k^0(y, k_T) \Big/ \sigma_{incl} \sim C \int_{y_{min}}^{y_{max}} dy (e^y + e^{-y}). \tag{1}$$

Here C comes from integration on the transverse distribution, including the information of the concrete dynamics and structure of the QGM, but similar for different kinds of energetic quark jets, once the QGM fixed. For the case that pionization is dominant, this calculation can also include the contribution from the limiting fragmentation part, by a slightly modified value of y_{min}, y_{max}, based on the mean value theorem of integration. For central A-A collision in the laboratory frame, neglecting the asymmetry of its thermal movements and assuming the (left-right) symmetry of its longitudinal expansion, in average the QGM can be taken as at rest. So the rapidity y of the created quanta can take values from $y_{min} \sim 0$ to $y_{max} \sim A \ln(E/M)$. Here E, M, are respectively energy and mass of the preliminary jet and $A(> 0)$ is a constant. A can depend on the dynamics, structure and size of the QGM. We then conclude, without concrete values of the constant C and A:

1) $< \Delta E > /E \simeq C E^{A-1}/M^A$. This power behaviour of the dependence on preliminary jet energy relies on the concrete width of the rapidity plateau, and can rise ($A > 1$) or fall ($0 < A < 1$), comparing to the LPM behaviour $\sim 1/E$.

2) The ratio between energy losses of two kinds of jets with same energy E but respective average mass M_1, M_2 is $r_{12}(E) =< \Delta E >_1 / < \Delta E_2 >\simeq (M_2/M_1)^A$. The details of the QGM

(density, temperature, size, etc.) cancels.

3) M_1, M_2 are average masses of the preliminary jets ("dressed parton") rather than those of the partons initializing the jets. The initial quark mass can introduce modifications to the average jet mass, but the difference is dramatically reduced by dressing quark mass to be jet mass[a]. This is exactly what RHIC data[4] indicate. Furthermore, the mass of light quark jet can always be an infrared-safe hard scale for perturbative QCD, while the light quark mass can not.

A feasible and decisive test of the above physical picture is to observe the open c, b hadrons (or more practical, non-photonic leptons for the present experimental condition). To measure their nuclear modification factor R_{AA} in the modest rapidity interval (e.g., as for J/Ψ measured by PHENIX, $|y| = 1.2 \sim 2.2$) for central heavy ion collision at RHIC or LHC. Then comparing with the data around $y = 0$. From the above discussion, especially point 1), combining with the bremsstrahlung energy loss, at a linear approximation of the dependence of ΔE on E, we get the similar expression for energy loss as in QED: $\Delta E = \alpha + \beta E$. This means the larger of the jet energy, the more energy lost. So one can predict more suppressed transverse momentum spectrum hence smaller R_{AA} at modest rapidity, because for a definite p_T, one has larger total energy at modest rapidity. This is in fact implied by the J/Ψ spectrum (though now mostly taken as indication of regeneration)[11]. An even clear indication is observed in the central Cu-Cu collision, which also seems a puzzle at first sight. The transverse spectrum of heavy flavour muon at rapidity region $1.4 \sim 1.9$ (PHENIX) is more suppressed than those of the light quark at $y \sim 0$ (STAR)[12]. As is known (and from our physical picture in this paper), the heavy flavour lepton is almost the same suppressed as the light quark but hardly more. So apart from systematics between these two collaborations (and those between electron and muon), and ignoring the rare possibly exceptional strange behaviour that heavy flavour lepton is more suppressed than light hadrons in central Cu-Cu collisions, this implies that even light hadrons may demonstrate such a property. For observing and comparing the open heavy hadrons (or their offspring leptons) in various rapidity region, an even significant signal can be found.

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[a] By investigating the average jet mass in 2-jet events in e^+-e^- annihilation for various initial quarks and various center of mass energies, employing Durham algorithm in Pythia/Jetset, we find that the proportion of average masses for light, charm and bottom jets, $M_{jl} : M_{jc} : M_{jb}$, varies from $1 : 1.01 : 1.26$ to $1 : 1.01 : 1.08$, for jet energies from $6GeV$ to $20GeV$.