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PION RADIATION BY HOT QUARK-GLUON PLASMA *)

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ABSTRACT

Highly excited hadronic matter consisting of quarks and gluons radiates an important fraction of its excitation energy by pion emission.

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We consider here an approximately spherical region of the perturbative QCD vacuum, filled with quarks, antiquarks and gluons. The particle densities are assumed to be reasonably well described by local thermal and chemical equilibrium distributions. The basis for these assumptions is the point that the mean free path of a colour-charged particle in the plasma is of the order of 1/3 - 1/2 fm. Outside the perturbation region, coloured particles cannot exist and hence any matter found there is in the form of colourless hadrons. Even though indirect evidence supports the picture of the true and perturbative QCD states, we must remember that no direct evidence is available as of now. We regard the observation of the quark-gluon plasma state as the most direct confirmation of the ideas about the nature of strong interactions and quark confinement.

For an impenetrable surface between the perturbative and true vacuum states, the inside thermal and degeneracy pressure would lead to an expansion until either pressure equilibrium or a phase transition into individual hadrons is reached. However, if the surface is penetrable, i.e., if it allows transmission of momentum and energy (but not colour) from the inside, then this can lead to a substantial internal energy and pressure loss by radiation -- the pressure acting on the surface is reduced, as not all the momentum impinging on the surface has to be reflected. On first thought, the microscopic mechanism for this transmission arises in the following manner: when a fast quark or antiquark hits the boundary, a jet-like structure filled with colour field flux, i.e., a fluxtube might be formed. For sufficiently high quark momentum, this tube, instead of retracting, splits by $q\bar{q}$ pair creation. The leading particle associates with the antiparticle of the pair to form a meson, while the remaining pair particle may retract into the plasma. This microscopic picture1),2) suffers from several difficulties, in particular as far as pion radiation is concerned.

Before turning to the results of Ref. 1), we wish to discuss here the reasons for these difficulties. We first note that a pion is not an average $q\bar{q}$ bag with a mass of several hundred MeV like, e.g., the ρ meson. Any proposed microscopic mechanism for pion production must take into account the small mass of the produced final state, i.e., the strong $q\bar{q}$ binding effects and the rôle of the pion as Goldstone meson. These complex pionic structure effects have not been included in the presently available microscopic calculation2). Therefore, the results of Ref. 2) should be applied at best to the production of the heavy mesons. However, we see a further difficulty of principle when generalizing results of Ref. 3) to the particle radiation problem. This has to do with the necessity of conservation of the energy and the momentum during the string evolution. In particular, part of the energy used to extend the string (with the vacuum) does not require a momentum transfer. This excess momentum must be carried by additional degrees of freedom, which are not included in the present models.

Therefore, in the present qualitative context, we prefer to develop a quantitative model suitable for surface temperatures of 160 - 220 MeV and moderate baryon densities, so that the particle density is less than ∿10 particles/fm^3. Under these circumstances, surface collisions involving more than one particle per fm^2 are rare. Hence we can limit ourselves to consider sequential one-particle events. We assume$^{1)}$ that in order for the surface collision to lead to pion emission, the particle momentum normal to the surface must exceed a certain threshold. This momentum has to be larger than the normal momentum of the emitted pion. We take this quark threshold momentum p_M to be of the order of 1/4 GeV/c and observe that the results are quite insensitive to this choice, as well as to the actual shape of the threshold function θ describing the probability of pion emission. However, we note that the string breaking calculations of Ref. 2) would be reproduced only if the choice of $p_M \sim 700$ MeV is made.

The energy per unit surface and unit time that leaves the quark-gluon plasma is therefore simply given by

$$\frac{d^3E}{d^2Adt} = g \int \frac{d^3p}{(2\pi)^3}\, \rho(p) f(E)\; E(p)\theta(p)\, \frac{d^3V}{d^2Adt} \tag{1}$$

where $g = 12$ is the degeneracy of the light quarks. The differential is the normal velocity of particles impinging on the surface. The energy leaving the plasma region is not the total energy contained in the leading particle and we include in (1) the efficiency factor f. A naïve degree of freedom counting leads to $f \approx 2/3$. $\rho(p)$ is the phase space quark and antiquark particle density. We observe here that the presence of a net baryon number in the plasma enhances ρ and therefore the particle radiation. In view of the uncertainties it is sufficient to expand the Fermi distributions and to retain only the Boltzman term

$$\rho(p) \approx 2\cosh(\mu/T)\ e^{-\sqrt{p_{\parallel}{}^2+p_{\perp}{}^2}/T} \quad . \tag{2}$$

For $\mu/T \simeq 1.5$ the effect of radiation is enhanced by a factor 2.4 as compared with a baryonless plasma. Combining Eqs. (1) and (2), we obtain the generalized Stefan-Bolztman (SB) law:

$$\frac{d^3E}{d^2Adt} = \bar{f}\, \frac{g}{2\pi^2} \cosh(\mu/T)\ T^4\ 3e^{-p_M/T} \left(\frac{1}{3}\left(\frac{p_M}{T}\right)^2 + \left(\frac{p_M}{T}\right) + 1\right) . \tag{3}$$

the SB limit is recovered for $p_M \to 0$. The deviation of Eq. (3) from SB is significant for the evolution of the plasma, but nonetheless both quantities are of the same order of magnitude. In Fig. 1 we show the cooling rate calculated from Eq. (3) for two choices of p_M as a function of the surface temperature T, choosing $\mu/T = 1$.

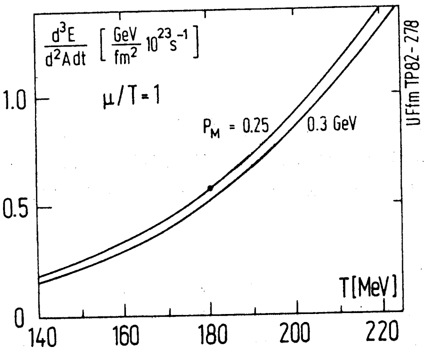

Fig. 1: Surface brightness of a quark-gluon plasma as function of the temperature for several cut-offs p_M at fixed $\mu/T = 1$. The dot indicates the parameters of our numerical example.

To appreciate the physical importance of these results, we now discuss the rate of energy loss through a surface A, assuming $T = 180$ MeV, $\mu = T$. First we find

$$\frac{dE}{dt} = A\ 0.58\ \frac{\text{GeV}}{\text{fm}^2}\ 10^{+23}\ \text{sec}^{-1} \quad .$$

This is a very large energy loss rate ! For example, through the surface of a sphere with a radius of 4 fm, the energy loss per $\Delta t = 2 \times 10^{-23}$ sec is 260 GeV. The available energy contained in such a sphere at 2.1 GeV/fm^3 (1.4 GeV/fm^3 available energy density) is 380 GeV. This shows that during the minimum estimated lifetime of the plasma, a substantial part of plasma energy can be radiated by the surface. We have added here the word "available" since at the chosen $\mu - T$ values the actual energy density is higher by 0.7 GeV/fm^3, in order to allow for the 150 baryons $(\mu \neq 0)$ present.

To conclude we note that those particles which penetrate the surface do not exert their full force on it. In particular one can show$^{1)}$ that the quark pressure is substantially reduced and is given by

$$\bar{P}_q = P_q \left(1 - f\ \frac{P_q(p_\perp > p_M)}{P_q} \right) \cong 0.4\ P_q \quad . \tag{4}$$

Since the quark pressure is about twice as large as the glue pressure, only about 60% of the internal pressure is felt by the surface.

The physical distinction between the cooling by pion radiation and by expansion resides in the reduction of the temperature without a significant increase of the plasma volume. Here we have demonstrated that the pion radiation is an essential feature controlling the evolution of a hot baryon-rich quark-gluon plasma droplet.

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