Modification of the quasiparticle damping rate in presence of flow in hot QCD plasma

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Introduction

In recent years the quasiparticle damping rate (Γ) has been calculated by several authors both in quantum chromodyamic (QCD) and quantum electrodynamic (QED) plasmas. In reference [1] the authors have shown in case of QED, the electric contribution to the quasiparticle damping rate with plasma screening effects is finite and is of the order $\Gamma_{long} \sim g^2T$ whereas the transverse part remains divergent. This is due to the fact that the later is only dynamically screened. The authors had to develop another resummation scheme to obtain a finite result [1]. In case of QCD similar problem in hot plasma can be removed by assuming a 'magnetic mass' for the gluons.

We aim here to calculate the quark damping rate in hot QCD plasma in presence of flow, whereas in the above cited calculation an equilibrium situation for the bath particles is assumed. The equilibrium condition of the bath particles is true only when there exists no velocity or temperature gradient in the plasma and there is no external force also. In the present context, we take into consider the existence of the non-zero velocity gradient *i.e* flow in the plasma. Under such scenario, one can no longer assume that the bath particles follow the ordinary equilibrium Bose-Einstein or Fermi-Dirac distributions for the interacting bosons or fermions respectively. The situation is quite similar to what one encounters for the calculation of the transport quantities like coefficient of viscosity or conductivity etc.

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Formalism

We first recall that, the calculation of decay width in plasma is directly related to the collision integral of the Boltzmann equation given by the following equation:

$$\left(\frac{\partial}{\partial t} + \mathbf{v_p}.\nabla_\mathbf{r} + \mathbf{F}.\nabla_\mathbf{p}\right) n_p = -\mathcal{C}[n_p], \quad (1)$$

here, $\mathbf{F}$ is the external force, $\mathbf{p}$ is the momentum of the quasiparticle. The right hand side of the equation is the collision integral. For the relativistic plasma, $\mathbf{v_p} = \hat{\mathbf{p}} = \mathbf{p}/|\mathbf{p}|$. If n_p is considered to be slightly out of equilibrium *i.e* $n_p = n_p^{eq} + \delta n_p$, in relaxation time approximation the solution of the Eq.(1) becomes $n_p(t) = n_p(0)\mathrm{e}^{-\Gamma_p t}$, where Γ_p is the damping rate of the quark moving with the momentum $\mathbf{p}$ related to the inverse life time τ_p^{-1}. Since, the distribution function has two parts one equilibrium and the other out of equilibrium the collision integral $\mathcal{C}[n_p]$ also consists of two parts, $\mathcal{C}[n_p] = \mathcal{C}^{eq}[n_p] + \mathcal{C}^{non-eq}[n_p]$. The general expression for the damping rate when four particles taking part in a two body scattering, are out of equilibrium is,

$$\begin{aligned}\Gamma(p) = \Big(\int_{k,p,p'} \Big[\delta n_p \Big(n_k(1 \pm n_{p'})(1 \pm n_{k'}) \\ \mp n_{p'} n_{k'}(1 \pm n_k)\Big) \\ +\delta n_k \Big(n_p(1 \pm n_{p'})(1 \pm n_{k'}) \mp n_{p'} n_{k'}(1 \pm n_p)\Big) \\ -\delta n_{p'} \left(n_{k'}(1 \pm n_p)(1 \pm n_k) \mp n_p n_k(1 \pm n_{k'})\right) \\ -\delta n_{k'} \Big(n_{p'}(1 \pm n_p)(1 \pm n_k) \mp n_p n_k(1 \pm n_{p'})\Big) \Big] \\ (2\pi)^4 \delta^4(p + k - p' - k')|M|^2\Big)/\delta n_p. \quad (2)\end{aligned}$$

In the above equation it is evident that if we put $\delta n_k = \delta n_{p'} = \delta n_{k'} = 0$, then we get back the usual expression for the damping rate when only one particle is out of equilibrium. Now, to proceed further we have to know the explicit form of δn_i $(i = p, k, p^{'}, k^{'})$. The non-equilibrium distribution function takes different form depending upon the problem considered. In the present case we take the distribution function as [2, 3],

$$\delta n_i = C\frac{\eta}{s}\frac{\partial n_i}{\partial p_i}\Phi_{i,xy}\mathcal{X}_{xy} \tag{3}$$

where, $\Phi_{i,xy} = \hat{p}_{i,x}\hat{p}_{i,y}f(p/T)$ and C is some constant. In the presence of a small shear flow $u(y)$ in the x direction $\mathcal{X}_{xy} = \partial u_x/\partial y$, $f(p/T)$ is some rotationally invariant function depending only on the energy of the excitation which has to be determined from the variational calculation of the Boltzmann equation [2, 3]. But a much simpler and standard way is to take the trial function in the viscous process as, $f(p/T) = (p/T)^2$ [2]. With the help of all these expressions mentioned above the damping rate takes the following form,

$$\begin{aligned}\Gamma(p) &= \frac{T^4}{(2\pi)^4p^4}\int_0^{\infty} q^2dqk^2dk \\ &\int_{-1}^{1} d\cos\theta d\cos\theta_{kq}\int_0^{2\pi} d\phi n_k(1\pm n_k^{'})|M|^2 \\ &\delta(p+k-p^{'}-k^{'})[\Phi_{xy}(\mathbf{p})+\Phi_{xy}(\mathbf{k}) \\ &-\Phi_{xy}(\mathbf{p}^{'})-\Phi_{xy}(\mathbf{k}^{'})]^2. \end{aligned} \tag{4}$$

Considering the small angle scattering limit which is a very reasonable assumption in the present context [3], one can easily obtain the square bracketed term in the above equation. The terms which actually contribute to the damping rate are the following,

$$\begin{aligned} &[\Phi_{xy}(\mathbf{p})-\Phi_{xy}(\mathbf{p}^{'})]^2 \\ &= \omega^2[f(p)']^2 + 3\frac{q^2-\omega^2}{p^2}[f(p)]^2, \\ &[\Phi_{xy}(\mathbf{k})-\Phi_{xy}(\mathbf{k}^{'})]^2 \\ &= \omega^2[f(k)']^2 + 3\frac{q^2-\omega^2}{p^2}[f(k)]^2. \end{aligned} \tag{5}$$

Upto now, we have not made any reference to the interaction which is contained in the matrix amplitude. For QCD plasma, with the dressed propagator for the soft sector the matrix amplitude squared for the quark-quark scattering takes the following form,

$$|M_{qq}|^2 = g^4\frac{4}{9}\left[\frac{1}{(q^2+\Pi_L)^2} + \frac{(1-x^2)^2\cos^2\phi}{(q^2-\omega^2+\Pi_T)^2}\right].$$

Using the Eqs.(4, 5, 6,) the final expression for the damping rate in presence of flow in the medium takes the following form,

$$\begin{aligned}\Gamma(p) &= g^4\left(\frac{5T^3}{54\pi p^2}+\frac{7\pi T^5}{54p^4}\right)\left[\log\left|\frac{2}{\sqrt{\pi}}\right|\right. \\ &\left.+2\log\left|\frac{q_{max}}{m_D}\right| - \frac{1}{30}\right]. \end{aligned} \tag{6}$$

From the kinematics the q_{max} here can be chosen as T [2]. From the final expression it is evident that at high temperature in presence of flow in the medium, quasiparticle damping rate turns out to be finite and logarithmic in nature.

Summary and Conclusion

To summarize we have derived an expression for the quark damping rate in QCD plasma in presence of flow. The quark damping rate in presence of a velocity gradient differs from the usual damping rate because of the presence of $\Phi_{xy}(p)$ terms which in turn, brings an extra ω^2 term in the numerator that changes the infrared behaviour of Γ completely. It is important to note also that Γ in the present context is independent of the coefficient of viscosity η and the magnitude of the flow gradient, although the distribution functions contain both the terms.

References

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