Freeze-out Condition of Relativistic e^-, e^+, γ-plasma ◇

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For an expanding drop of plasma there is the freeze-out size R where the particle density $\rho \propto 1/R^3$ decrease allows the free-out-streaming of all particles, since the scattering length $l \propto 1/(\sigma\rho)$ grows with R^3. Here we consider this freeze-out condition for a relativistic e^-, e^+, γ plasma. The conventional wisdom from keV temperature 'fusion' domain implies that an opaque plasma drop is not possible without 100's of MJ of energy.

Here we demonstrate a new temperature domain in which opaque plasma drops are possible for the energy content of $\cong 0.5\,\mathrm{kJ}$ with a radius in a range of $R = 2 \div 10$ nm, at a temperature at the scale of MeV. This new and interesting plasma domain arises since for $T > m_e$ the density of electron-positron pairs grows rapidly and the scattering length l accordingly decreases rapidly. These physical conditions should become accessible in the foreseeable future upon the development of wavelength compression technology employing an optical wavelength laser beam reflected from a relativistic mirror, generated by a pulsed high intensity laser [1].

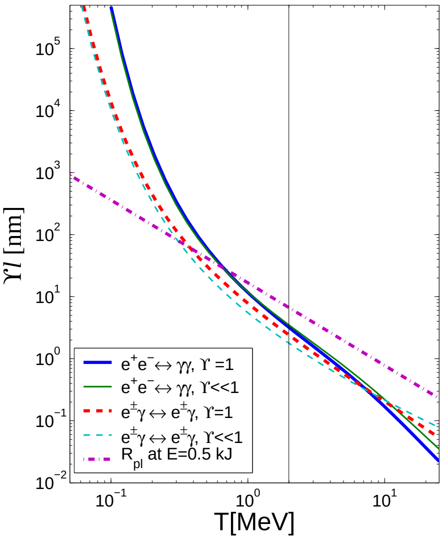

Fig. 1: $l\Upsilon$ for Compton scattering and pair production at a fugacity $\Upsilon = 1$ (thick dashed and solid lines) and $\Upsilon = 0.1$ (thin dashed and solid lines), as a functions of temperature T; dot-dashed line: the radius R of equilibrium ($\Upsilon = 1$) plasma at an energy 0.5 kJ.

We study the magnitude of the mean free path length l of a γ for Compton scattering and/or pair production assuming thermal equilibrium in the plasma drop. The plasma drop is opaque for $R >> l$. By comparing l with plasma size R at a given energy content we determine when thermal equilibrium can be achieved by Compton scattering and/or by pair production and annihilation. We take into account relativistic motion and quantum effects in dense medium [2,3]. The relativistically invariant quantum distribution function $f_{[e,\gamma]} = 1/(\Upsilon_{[e,\gamma]} e^{(u \cdot p_{e,\gamma})/T} \pm 1)$ involves the scalar product of the particle 4-momentum p_i^μ with the local 4-vector of velocity u^μ. We assume here that in the temperature domain of interest the the e^+e^--pair density dominates any initial electron density and thus $n_{e^-} \simeq n_{e^+}$.

A deviation from the thermal equilibrium is normally described introducing the fugacity Υ. In chemical equilibrium $\Upsilon_e = \Upsilon_\gamma = 1$. In figure 1 we show the product of Υ with l as a function of T for e^+e^- pair production reaction, i.e. $\Upsilon l_{\gamma\gamma}$, and Compton scattering $\Upsilon l_{e\gamma}$. The results were obtained for $\Upsilon = 1$ (thick dashed and solid lines, respectively) and $\Upsilon = 0.1$ (thin dashed and solid lines, respectively). We note that for $\Upsilon << 1$ there is no quantum effect in plasma, the free mean path l of photon scales exactly with $\propto \Upsilon^{-1}$. The lines shown in figure 1 for the two values of Υ are not identical due to the appearance of quantum effects at $\Upsilon \to 1$.

The effects of medium on reaction rate comes from statistic of initial particles and also Fermi blocking and/or Bose enhancement in final state. For electron-positron pair production the reaction rate and thus $l_{\gamma\gamma}$ is suppressed at $\Upsilon = 1$ by dominating effect of Bose statistic of photons in the initial state. Both quantum effects, Bose and Fermi statistic, contribute to the Compton mean free path. We see that $l_{\gamma\gamma} < l_{e\gamma}$ at $T > 8$ MeV for $\Upsilon = 1$ and at $T > 10$ MeV for $\Upsilon << 1$ and therefore the thermal equilibrium can be established by pair production at $T > 8$ MeV, at the same time for pairs and for photons.

Comparing l to the plasma drop size R_{pl}, dash-dot line in figure 1, we recognize that a plasma drop can be produced at an energy 0.5 kJ for $R < 7$ nm and $T > 2$ MeV. Note that at a higher temperature the opaque plasma can be created at the total plasma energy smaller than 0.5 kJ, since smaller plasma drop size is opaque, as seen in figure 1.

We find that the pair production and/or annihilation relaxation time in particle collisions is $\tau = 2\,10^{-2}$ fs $<< 2R/c$ at $T = 2$ MeV favoring formation of a thermally equilibrated system. However, the small drop of pair plasma is probably formed by strong electromagnetic fields sparking pairs in context of the Schwinger mechanism yet at a considerably shorter time scale [4].

To summarize, our main result illustrated in figure 1 is that at a temperature $T > 2$ MeV the equilibrium plasma production with a relatively small energy $E < 0.5$ kJ pulse may be possible. The challenge is to focus the laser energy into the volume of size $R < 10$ nm at which time also we generate the strong electric fields capable to produce the high density of pairs in the available time.

References

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