Pion and Muon Production in e^-, e^+, γ-Plasma ◇

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The formation of a relativistic (temperature in MeV range, $T > m_e$), electron-positron-photon e^-, e^+, γ QED plasma in the laboratory using ultra-short pulse lasers is one of the topics of forthcoming experimental effort [1]. We explored the production of strongly interacting pions $\pi^\pm, \pi^0$ ($m_\pi c^2 \lesssim 140$ MeV), and the 'heavy electron' muons $\mu^\pm (m_\mu c^2 \lesssim 106$ MeV) where $m \gg T$. Information about the early stages of the plasma, and even the pre-equilibrium state should become accessible in this way [2].

π^0 in the QED plasma are produced predominantly in the thermal two photon fusion:$\gamma + \gamma \to \pi^0$. The resulting master equation for pion number evolution is:

$$\frac{dN_{\pi^0}}{V dt} = (1 - \Upsilon_{\pi^0}) R_{\gamma\gamma\to\pi^0}; \quad \text{where} \qquad (1)$$

$$N_{\pi^0} = V \int \frac{d^3p}{(2\pi)^3} \frac{1}{\Upsilon_{\pi^0}^{-1} e^{\sqrt{m_{\pi^0}^2 + p^2}/T} - 1}. \qquad (2)$$

$R_{\gamma\gamma\to\pi^0}$ is the (Lorentz) invariant π^0 production rate per unit time and volume in photon fusion, and can be expressed in terms of the π^0 lifespan and photon density. The fugacity Υ_{π_0} evolves with time, and we reach chemical equilibrium for $\Upsilon_{\pi_0} \to 1$ where the time variation of density due to production and decay vanishes.

In the plasma under consideration, muons can be produced in the reactions: $\gamma + \gamma \to \mu^+ + \mu^-$, $e^+ + e^- \to \mu^+ + \mu^-$. The master evolution equation takes the form:

$$\frac{1}{V}\frac{dN_\mu}{dt} = (1 - \Upsilon_\mu^2)\left(R_{\gamma\gamma\to\mu^+\mu^-} + R_{e^+e^-\gamma\to\mu^+\mu^-}\right). \qquad (3)$$

$\pi^\pm$ are produced dominantly in charge exchange scattering: $\pi^0 + \pi^0 \to \pi^+ + \pi^-$, as well as in two photon, and in electron-positron fusion processes. In figure 1 we show relaxation time τ for the processes considered as function of temperature $T \in \{3, 50\}$ MeV.

In table 1 we show the values of key reaction rates R and relaxation times τ at $T = 5$ MeV, while in figure 1 we show the relaxation time τ needed to achieve chemical yield equilibrium for the different processes considered as function of temperature $T \in \{3, 50\}$ MeV. τ is defined as follows in two body reactions, e.g.:

$$\tau_{\pi^0\pi^0\to\pi^+\pi^-} = \frac{\Upsilon_{\pi^0}}{2} \frac{dn_{\pi^\pm}/d\Upsilon_{\pi^\pm}}{R_{\pi^0\pi^0\to\pi^+\pi^-}}. \qquad (4)$$

Table 1: Reaction rates, relaxation times at $T = 5$ MeV

reaction	τ [as]	R [nm^{-3}fs^{-1}]
$\gamma\gamma \leftrightarrow \pi_0$	$8.82\,10^2$	$3.3\,10^3$
$e^+e^- \leftrightarrow \mu^+\mu^-$	$1.2\,10^{10}$	$3.2\,10^{-3}$
$\gamma\gamma \leftrightarrow \mu^+\mu^-$	$1.0\,10^{10}$	$3.7\,10^{-3}$
$\pi^0\pi^0 \leftrightarrow \pi^+\pi^-$	$2.9\,10^{12}$	$2.1\,10^{-8}$
$\gamma\gamma \leftrightarrow \pi^+\pi^-$	$6.4\,10^{13}$	$9.7\,10^{-10}$

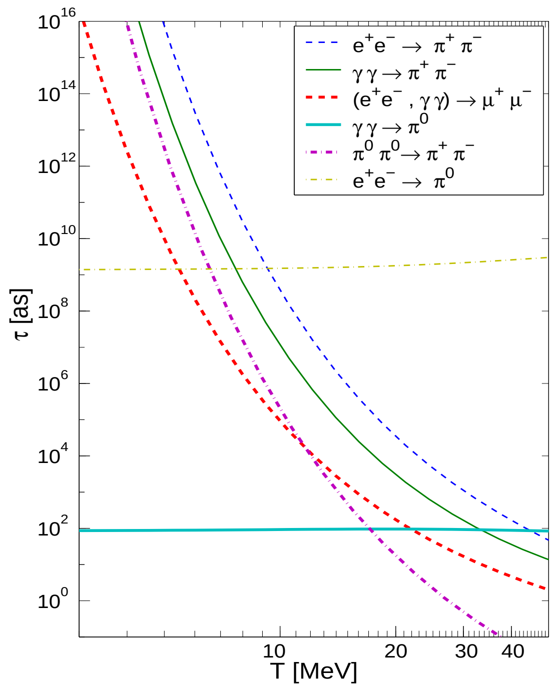

Fig. 1: The relaxation time τ for the different pion and muon production channels, as functions of the plasma temperature T.

A plasma drop of radius 2nm at $T = 10$ MeV contains 13 kJ energy. This is the expected energy content of a light pulse at ELI (European Light Infrastructure [3]) with a pulse length of about $\Delta t = 10^{-14}s$. A thousandth harmonic may be focused to this nm scale. Thus muons and pions can indeed be made one day with lasers. However, the detection of π^0 in a QED plasma environment is not an easy task – the π^0 decay into two 67.5 MeV γ (+ thermal Doppler shift motion) produces a characteristic signature. However, the radiation debris of the plasma is a difficult background. Muons and also charged pions are comparatively easy to observe given their longer lifespan.

For the far future we note that should one find a way to 'focus' the laser energy to near nuclear dimensions, we may reach $T = 150$ GeV, a consideration which led the authors of Refs. [1] to suggest that the electro-weak symmetry restoration transition may be one day achieved using ultra-short laser pulses.

References

[1] T. Tajima, G. Mourou and S.V. Bulanov, Phys. Mod. Phys. **78** (2006) 309
T. Tajima and G. Mourou Phys. Rev. ST Accel. Beams **5** (2002) 031301
[2] I. Kuznetsova, D. Habs and J. Rafelski, arXiv:0803.1588 [hep-ph].
[3] See CNRS press release of Feb. 27, 2008 at: http://www2.cnrs.fr/en/1125.htm

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