CAUSAL HEAT TRANSPORT INDUCED BY ZEPTOSECOND LASER PULSES

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Abstract

In this paper the thermal phenomena induced by zeptosecond (10^{-21} s) laser pulses are discussed. Considering the theoretical proposal of the *lasetron*, the Heaviside equation for heat transport on zeptosecond time scale was formulated. In the paper the modified Schrödinger equation (Lasers in Engineering, **12**, (2002), 53) for quantum phenomena on the zeptosecond time scale was also discussed.

Keywords: Quantum heat transport; Zeptosecond laser pulses; Modified Schrödinger equation.

1 Introduction

In paper [1] was theoretically demonstrated that $10^{-21} - 10^{-22}$ s (zeptosecond and subzeptosecond) laser pulses can be generated using petawatt lasers, while already available terawatt lasers may generate subattosecond pulses of $\sim 10^{-19}$ s. The pulses will be radiated by ultrarelativistic electrons driven by circularly polarized high-intensity laser fields. They are basically reminiscent to synchroton radiation. The major distinct feature is the forced synchronization of all radiating electrons by the driving laser field. Radiation of such a synchronized bunch would be viewed by an observer at any point in the rotation plane as huge pulses/burst of electromagnetic field as short as:

$$\Delta t \sim \frac{1}{2\omega_L \gamma^3}, \tag{1}$$

where γ is the electron's relativistic factor. With $\lambda_L = (2\pi c)/(\omega_L) \sim 1\mu$m and $\gamma \sim 64$ (attainable with a petawatt laser) $\Delta t \sim 10^{-21}$ s. Such a system can be call *lasetron* [1]. It can be achieved by placing a solid particle or a piece of wire of subwavelength cross section in the focal plane of a superenergetic laser.

The *lasetron* as a source of the zeptosecond laser pulses open the new possibility of the investigation of the superfast thermal processes. In this paper we discuss the structure of the Heaviside equation for the description of the interaction of the *zs* laser pulses with matter.

In addition in the paper we investigate the generalized Schrödinger equation which structure changes (in comparison to Schrödinger equation) for zeptosecond time scale. Both equations contain additional term proportional to the relaxation time.

The models of thermal processes with $\tau \neq 0$ we will call the causal models of the thermal phenomena in the opposition to noncausal models with $\tau = 0$. The physical background for the differentiation of the causal and noncausal models stems from the observation that for $\tau = 0$ velocity of the propagation of the interaction $v \to \infty$, and $v/c \to \infty$ (c = light velocity) in complete disagreement with special relativity theory.

2 Heat transport in zeptosecond (10^{-21} s) time scale

Ultrashort electromagnetic pulses have always been a great interest, largely as a means of investigating and controlling ever faster processes on different scales: molecular, atomic and recently nuclear. Recent proposals [1] explored various method to attaining the shortest subfemtosecond ($10^{-16} - 10^{-17}$) laser pulses of atomic time-scale duration. In the most recent breakthrough work [2] the train of 0.25 fs pulses have been observed experimentally. Time-resolved measurement with these pulses are able to trace dynamics of molecular structure, but fail to capture electronic processes occurring on an attosecond time scale. Very recently [3] M. Hentschel at al. traced electronic dynamics with of ≤ 150 as (10^{-18} s) by using a subfemtosecond soft X-ray pulse and a few-cycle visible light pulse. The results presented in paper [3] indicates an attosecond response of the atomic system, a soft X-ray pulse duration of 650 ± 150 as and an attosecond synchronism of the soft X-ray pulse with the light field. The demonstrated experimental tools and techniques open the door to attosecond spectroscopy of bound electrons.

In paper [1] A. E. Kaplan and P. L. Shkolnikov demonstrated theoretically that zeptosecond (zs), 10^{-21} s, pulses can in fact be generated using petawatt lasers while already available terawatt lasers may generate subattosecond pulses of 10^{-19} s. The pulses will be radiated by ultrarelativistic electrons driven by circularly polarized high-intensity laser fields.

In our paper we propose the relativistic Heaviside equation for the study the thermal process induced by laser pulses with time duration $\Delta t < \tau$ where τ is the characteristic relaxation time:

$$\frac{1}{v^2}\frac{\partial^2 T}{\partial t^2} + \frac{m}{\hbar}\frac{\partial T}{\partial t} + \frac{2Vm}{\hbar^2}T - \nabla^2 T = 0, \tag{2}$$

$$v = \alpha c, \qquad \tau = \frac{\hbar}{m\alpha^2 c^2}.$$

In equation (2) m is the heat carrier mass and α is strength constant for electromagnetic ($\alpha = 1/(137)$) or strong interaction ($\alpha = 0.15$), V is the potential energy, c – velocity of light.

In paper [4] it was shown that Heaviside diffusion equation (2) can be obtained within the frame of the correlated random walk (CRW) of the Brownian motion. As was shown in paper [4] the average displacement of the Brownian particle (for $V = 0$) is described by formula:

$$< x^2 >= \frac{2\hbar\tau}{m}\left[\frac{t}{\tau} - \left(1 - e^{-\frac{t}{\tau}}\right)\right]. \tag{3}$$

For $t > \tau$ formula (3) gives

$$< x^2 >= \frac{2\hbar}{m}t. \tag{4}$$

Formula (4) describes the quantum diffusion of heat carriers (*heatons*) with quantum coefficient $D = \hbar/m$.

For $t \leq \tau$ one obtains from formula (3)

$$< x^2 >= \alpha^2 c^2 t^2. \tag{5}$$

Formula (5) describes the *ballistic* motion of a *heaton* with velocity $v \sim \alpha c$. For $t < \tau$ (and $V = 0$) equation (2) has the form of the wave equation:

$$\frac{1}{v^2}\frac{\partial^2 T}{\partial t^2} = \nabla^2 T. \tag{6}$$

The maximum value of the thermal wave velocity can be equal c – the velocity of light. In that case the relaxation time is described by formula:

$$\tau = \frac{\hbar}{mc^2} = \frac{\Lambda}{c}, \tag{7}$$

where Λ denotes the reduced Compton wave length e.g. for electrons

$$\Lambda = \frac{\hbar}{mc}. \tag{8}$$

It is well known from quantum electrodynamics that quantum void fluctuations create and destroy virtual electron-positron pairs. These virtual electron-positron pairs have a characteristic life-time of the order $\Lambda/c \sim 10^{-21}$ s $= 1$ zs. The Compton wavelength Λ can be identified as the new mean free path since it is the typical distance covered by the virtual pair before its annihilation.

It is important to take into account the fact that for $\Delta t < \tau$ zs the *heatons* move with the velocity of light. It is worthwhile to realize that there exist models of elementary particles in which it is assumed that the electron propagates with the speed of light with certain chirality, except that at random times it flips both the direction of propagation (by 180^0) and handedness, the rate of such flips is precisely the mass m (in units $\hbar = c = 1$) [5],[6]. In the frame of the model developed in the present paper, the relaxation time for the interaction of *heatons* with voids is described by the formula $\tau = \Lambda/c = 1$ zs (for electrons).

In our paper [7] the generalized Schrödinger equation was formulated:

$$i\hbar\frac{\partial\Psi}{\partial t}=-\frac{\hbar^2}{2m}\nabla^2\Psi+V\Psi-\frac{2\hbar^2}{m\alpha^2c^2}\frac{\partial^2\Psi}{\partial t^2}. \tag{9}$$

Equation (9) can be written as:

$$i\hbar\frac{\partial\Psi}{\partial t}=-\frac{\hbar^2}{2m}\nabla^2\Psi+V\Psi-\frac{2\hbar}{\alpha^2}\frac{\Lambda}{c}\frac{\partial\Psi}{\partial t^2}. \tag{10}$$

In equation (10) the last term proportional to Λ/c:

$$-\frac{2\hbar}{\alpha^2}\frac{\Lambda}{c}\frac{\partial^2\Psi}{\partial t^2}. \tag{11}$$

describes the interaction of electrons with virtual positron-electron pairs in the void. This interaction can be investigated only with zeptosecond laser pulses emitted by *lasetron* [1]. In order to obtain Schrödinger equation:

$$i\hbar\frac{\partial\Psi}{\partial t}=-\frac{\hbar^2}{2m}\nabla^2\Psi+V\Psi,$$

we are forced to assume $\Lambda/c\rightarrow 0$ i.e. $c\rightarrow\infty$ (nonrelativistic approximation) or $\Lambda\rightarrow 0$, i.e. we exclude the change of photon wavelength in Compton experiment. Both assumption are not in agreement with experiment.

3 Conclusion

In the paper the master equation (Heaviside equation) for zeptosecond laser pulses was discussed. It was shown that the mean free path for relativistic heatons is of the order the Compton wavelength for electron scattered on virtual electron-positron pairs. Considering the generalized Schrödinger equation formulated in our earlier paper it was shown that additional term (with second order time derivative) is proportional to Compton wavelength. With zeptosecond laser pulses emitted by *lasetron* the influence of this term on thermal transport phenomena can be investigated.

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