Nuclear collective processes study with attosecond laser pulses

Janina Marciak-Kozłowska

and

Mirosław Kozłowski\textsuperscript{1}

Institute of Electron Technology, Al. Lotników 32/46, 02-Warsaw, Poland

\textsuperscript{1}Corresponding author, e-mail: MiroslawKozlowski@aster.pl,
http://www.fuw.edu.pl/~mirkoz
Abstract

In this paper the possibility of the excitation of collective nuclear motion with attosecond laser pulses is investigated. Following the results of our earlier results (Lasers in Engineering, 11 (2001), p. 259) the hyperbolic heat transport for nuclear matter is formulated and solved. It is shown that in the vicinity of the 30 MeV excitation energy the recollided electrons can excite the giant collective motions – thermal wave inside the nuclei.

Key words: Attosecond laser pulses; Electronuclear reactions; Thermal waves; Giant resonances.
1 Introduction

With attosecond lasers (1 as = $10^{-18}$ s) physicists and engineers are now close to controlling the motion of electrons on a timescale that is substantially shorter than the oscillation period of visible light. It is also possible with attosecond laser pulse to rip an electron wave-packet from the core of an atom and set it free with similar temporal precision.

Recently a laser configuration in which attosecond electron wave packets are ionized and accelerated to multi-MeV energies, was proposed [1]. This technique opens an avenue towards imaging attosecond dynamics of nuclear processes.

High laser intensity atomic and molecular physics is dominated by the recollision between and ionized electron and its parent ion. The electron is ionized near the peak of laser field, accelerated away from the ion and driven back to its parent ion once the field direction reverses. Recollision leads to nonsequential double ionization, high harmonic generation, and attosecond extreme ultraviolet and electron pulses [1].

In contrast the extension of laser induced recollision physics to relativistic energies is a long standing issue. The solution to this problem was achieved in paper [1]. The authors of the paper [1] show that the Lorentz force (which prevents recollision for relativistic electrons) is eliminated for two counter-propagating, equally handed, circularly polarized beams through the whole focal volume as long as the laser pulses are sufficiently long. In this configuration, the recollision energy is limited only by the maximum achievable laser intensity (currently $\sim 10^{23}$ W/cm$^3$).

The method presented in paper [1] will alter the physics anywhere relativistic laser fields interact with electrons. For example the attosecond laser pulses can resolve nuclear dynamics. In nuclear physics it opens novel possibilities in the study of decay and damping of nuclear dynamical processes such as giant resonances. It reveals information on fundamental nuclear properties, such as dissipation and viscosity in nuclei.
2 Relativistic hyperbolic heat transport equation for nuclear processes

In paper [3] relativistic hyperbolic transport equation (RHT) was formulated:

\[
\frac{1}{v^2} \frac{\partial^2 T}{\partial t^2} + \frac{m_0 \gamma}{\hbar} \frac{\partial T}{\partial t} = \nabla^2 T.
\] (1)

In equation (1) \(v\) is the velocity of heat waves, \(m_0\) is the mass of heat carrier (nucleon) and \(\gamma\) – the Lorentz factor, \(\gamma = \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}}\). As was shown in paper [1] the heat energy (heaton temperature) \(T_h\) can be defined as follows:

\[
T_h = m_0 \gamma v^2.
\] (2)

Considering that \(v\), thermal wave velocity equals [1]

\[
v = \alpha c.
\] (3)

where \(\alpha\) is the coupling constant for the interactions which generate the thermal wave (\(\alpha = 0.15\) for strong force) heaton temperature equals

\[
T_h = \frac{m_0 \alpha^2 c^2}{\sqrt{1 - \alpha^2}}.
\] (4)

From formula (4) one concludes that heaton temperature is the linear function of the mass \(m_0\) of the heat carrier. It is quite interesting to observe that the proportionality of \(T_h\) and heat carrier mass \(m_0\) was the first time observed in ultrahigh energy heavy ion reactions measured at CERN [4]. In paper [4] it was shown that temperature of pions, kaons and protons produced in Pb+Pb, S+S reactions are proportional to the mass of particles. Recently at Rutherford Appleton Laboratory (RAL) the VULCAN laser was used to produce the elementary particles: electrons and pions [5].

In the present paper the forced relativistic heat transport equation will be studied and solved. In paper [6] the damped thermal wave equation was developed:

\[
\frac{1}{v^2} \frac{\partial^2 T}{\partial t^2} + \frac{m}{h} \frac{\partial T}{\partial t} + \frac{2V m}{h^2} T - \nabla^2 T = 0.
\] (5)

The relativistic generalization of equation (5) is quite obvious:

\[
\frac{1}{v^2} \frac{\partial^2 T}{\partial t^2} + \frac{m_0 \gamma}{h} \frac{\partial T}{\partial t} + \frac{2V m_0 \gamma}{h^2} T - \nabla^2 T = 0.
\] (6)
It is worthwhile to note that in order to obtain nonrelativistic equation we put $\gamma = 1$.

The motion of charged nucleons in the nucleus is equivalent to the flow of an electric current in a loop of wire. With attosecond laser pulses we will be able to influence the current in the nucleon “wire”. This opens quite new perspective for the attosecond nuclear physics. The new equation (6) is the natural candidate for the master equation which can be used to the description of heat transport in nuclear matter.

When external force is present $F(x, t)$ the forced damped heat transport is obtained instead of equation (6) (in one dimensional case):

$$\frac{1}{v^2} \frac{\partial^2 T}{\partial t^2} + \frac{m_0 \gamma}{\hbar} \frac{\partial T}{\partial t} + \frac{2V m_0 \gamma}{\hbar^2} T - \frac{\partial^2 T}{\partial x^2} = F(x, t). \quad (7)$$

The hyperbolic relativistic quantum heat transport equation (RQHT), formula (7), describes the forced motion of heat carriers which undergo the scatterings ($\frac{m_0 \gamma}{\hbar} \frac{\partial T}{\partial t}$ term) and are influenced by potential ($\frac{2V m_0 \gamma}{\hbar^2} T$ term).

The solution of equation can be written as

$$T(x, t) = e^{-\frac{t}{\tau}} u(x, t), \quad (8)$$

where $\tau = \frac{\hbar}{(mv^2)}$ is the relaxation time. After substituting formula (8) to the equation (7) we obtain new equation

$$\frac{1}{v^2} \frac{\partial^2 u}{\partial t^2} - \frac{\partial^2 u}{\partial x^2} + qu(x, t) = e^{\frac{t}{\tau}} F(x, t), \quad (9)$$

and

$$q = \frac{2V m}{\hbar^2} - \left(\frac{mv}{2\hbar}\right)^2, \quad (10)$$

$$m = m_0 \gamma.$$ 

Equation (9) can be written as:

$$\frac{\partial^2 u}{\partial t^2} - v^2 \frac{\partial^2 u}{\partial x^2} + qv^2 u(x, t) = G(x, t), \quad (11)$$

where

$$G(x, t) = v^2 e^{\frac{t}{\tau}} F(x, t).$$
When $q > 0$ equation (11) is the forced Klein-Gordon (K-G) equation. The solution of the forced Klein-Gordon equation for the initial conditions:

$$u(x, 0) = f(x), \quad u_t(x, 0) = g(z)$$

has the form [4]:

$$u(x, t) = \frac{f(x - vt) + f(x + vt)}{2} + \frac{1}{2v} \int_{x-vt}^{x+vt} g(\zeta) J_0 \left[ q \sqrt{v^2 t^2 - (x - \zeta)^2} \right] d\zeta$$

$$- \frac{\sqrt{q} vt}{2} \int_{x-vt}^{x+vt} f(\zeta) \frac{J_1 \left[ q \sqrt{v^2 t^2 - (x - \zeta)^2} \right]}{\sqrt{v^2 t^2 - (x - \zeta)^2}} d\zeta$$

$$+ \frac{1}{2v} \int_0^{t'} \int_{x-v(t-t')}^{x+v(t-t')} G(\zeta, t') J_0 \left[ q \sqrt{v^2 (t - t')^2 - (x - \zeta)^2} \right] d\zeta dt'.$$

When $q < 0$ equation (11) is the forced modified Heaviside (telegraph) equation with the solution [5]:

$$u(x, t) = \frac{f(x - vt) + f(x + vt)}{2} - \frac{1}{2v} \int_{x-vt}^{x+vt} g(\zeta) J_0 \left[ -q \sqrt{v^2 t^2 - (x - \zeta)^2} \right] d\zeta$$

$$+ \frac{\sqrt{-q} vt}{2} \int_{x-vt}^{x+vt} f(\zeta) \frac{J_1 \left[ -q \sqrt{v^2 t^2 - (x - \zeta)^2} \right]}{\sqrt{v^2 t^2 - (x - \zeta)^2}} d\zeta$$

$$+ \frac{1}{2v} \int_0^{t'} \int_{x-v(t-t')}^{x+v(t-t')} G(\zeta, t') J_0 \left[ -q \sqrt{v^2 (t - t')^2 - (x - \zeta)^2} \right] d\zeta dt'.$$

When $q = 0$ equation (11) is the forced thermal equation [7]

$$\frac{\partial^2 u}{\partial t^2} - v^2 \frac{\partial^2 u}{\partial x^2} = G(x, t).$$

On the other hand one can say that equation (15) is the distortionless hyperbolic equation. The condition $q = 0$ can be rewrite as:

$$V \tau = \frac{\hbar}{8}.$$
The equation (16) is analogous to the Heisenberg uncertainty relations. Considering formula (2) equation (16) can be written as:

$$V = \frac{T_h}{8}, \quad V < T_h.$$  \hfill (17)

One can say that the distortionless waves can be generated only if $T_h > V$. For $T_h < V$, i.e., when the “Heisenberg rule” is broken, the shape of the thermal waves is changed.

We consider the initial and boundary value problem for the inhomogeneous thermal wave equation in semi-infinite interval [7]: that is

$$\frac{\partial^2 u}{\partial t^2} - v^2 \frac{\partial^2 u}{\partial x^2} = G(x, t), \quad 0 < x < \infty, \quad t > 0,$$  \hfill (18)

with initial condition:

$$u(x, 0) = f(x), \quad \frac{\partial u(x, 0)}{\partial t} = g(x), \quad 0 < x < \infty,$$

and boundary condition

$$au(0, t) - b \frac{\partial u(0, t)}{\partial x} = B(t), \quad t > 0,$$  \hfill (19)

where $a \geq 0, \ b \geq 0, \ a + b > 0$ (with $a$ and $b$ both equal to constants) and $F, f, g$ and $B$ are given functions. The solution of equation (18) is of the form [4]

$$u(x, t) = \begin{cases} 0, & x > vt, \\ \frac{v}{b} \int_0^{t-x/v} \exp \left[ \frac{va}{b} \left( y - t + \frac{x}{v} \right) \right] B(t) dt, & 0 < x < vt \end{cases}$$  \hfill (20)

In the special case where $f = g = F = 0$ we obtain the following solution of the initial and boundary value problem (19), (20):

$$u(x, t) = \begin{cases} 0, & x > vt, \\ \frac{v}{b} \int_0^{t-x/v} \exp \left[ \frac{va}{b} \left( y - t + \frac{x}{v} \right) \right] B(t) dt, & 0 < x < vt \end{cases}$$  \hfill (21)
if $b \neq 0$. If $a = 0$ and $b = 1$, we have:

$$u(x, t) = \begin{cases} 
0, & x > vt, \\
v \int_0^{t-\frac{x}{v}} B(y) dy, & 0 < x < vt 
\end{cases}$$

It can be concluded that the boundary condition (19) gives rise to a wave of the form $K \left( t - \frac{x}{v} \right)$ that travels to the right with speed $v$. For this reason the foregoing problem is often referred to as a signaling problem for the thermal waves.

3 Attosecond laser electronuclear spectroscopy

As was shown in paragraph 2 the master equation for collective (thermal wave) motion of nucleons has the form

$$\frac{\partial^2 u}{\partial t^2} - v^2 \frac{\partial^2 u}{\partial x^2} + qv^2 u(x, t) = G(x, t). \quad (22)$$

When we are looking for undistorted motion, $q \to 0$ i.e.:

$$\frac{2Vm}{\hbar^2} - \left( \frac{mv}{2\hbar} \right)^2 \to 0.$$ 

For $q = 0$ one obtain

$$V \tau = \frac{\hbar}{8}. \quad (23)$$

For nuclear collective motion $\tau = \frac{\hbar}{mv^2}$, $m$ is the nucleon mass and $v = \alpha_s c$, where $\alpha_s = 0.15$ [8] is the strong coupling constant. With the $m = 981 \frac{MeV}{c^2}$ one obtains from formula (23)

$$V = \frac{\hbar}{8\tau} \approx 30\text{MeV}. \quad (24)$$

As it is well known the 30 MeV energy range is the location of giant dipole resonances in nuclear matter [9].

As was shown in paper [2] for attosecond laser induced recollision of electrons with ions the energy of the electrons is of the order of 30 MeV for $Z \approx 20$ (where $Z$ is the atomic number of the ion). It means that with attosecond laser pulses the electronuclear giant resonances can be excited and investigated.
**Conclusion**

In this paper the interaction of the attosecond laser pulses with atoms was investigated. It is shown that recollided (after attoseconds pulse excitations) electrons can excite the thermal wave – giant resonances in nuclear matter. These electronuclear reactions can be investigated with hyperbolic nuclear thermal equation (18).
References

[1] T. Brabec and F. Kransz, *Rev. Mod. Phys.*, 72, (2000), p. 545.

[2] Nenad Milosevic et al., *Phys. Rev. Lett.*, 92, (2004), p. 013002-I.

[3] J. Marciak-Kozlowska, M. Kozlowski, *Lasers in Engineering*, 11, (2001), p. 259.

[4] I.G. Bearden et al., *Phys. Rev. Lett.*, 78, (1997), p. 2080.

[5] K. W. D. Ledingham and P.A. Norreys, *Contemporary Physics*, 40, (1999), p. 367.

[6] M. Kozlowski, J. Marciak-Kozlowska, *Lasers in Engineering*, 8, (1998), p. 11.

[7] E. Zauderer, *Partial Differential Equation of Applied Mathematics*, Second Edition, Wiley 1989.

[8] M. Kozlowski, J. Marciak-Kozlowska, *From Quarks to Bulk Matter*, Hadronic Press, USA (2001).

[9] G. F. Bertsch et al., *Rev. Mod. Phys.*, 55 (1983), p. 287.