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POSSIBILITY OF OBTAINING A POWERFUL NEUTRON SOURCE BY ACTION OF A LASER PULSE ON A COMPOUND TARGET

Yu.V. Afanas'ev, E.M. Belenov, O.N. Krokhin, and I.A. Poleuktov
P.N. Lebedev Physics Institute, USSR Academy of Sciences
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1. When a laser pulse acts on a condensed target containing D and DT atoms, a temperature $T \simeq 10$ keV and accordingly a large neutron yield $N_n \simeq 10^{16} - 10^{17}$ can be obtained if the total pulse energy is $W \simeq 10^5$ J [1]. The influence of light-element impurities was investigated in [2]. In the present paper we point out the possibility of obtaining a large neutron yield $N_n \simeq 10^{15}$ by applying a short laser pulse of duration $\tau \simeq 10^{-10}$ sec and energy $W \lesssim 10^4$ J on a condensed target consisting of a DT mixture with admixture (∿10%) of a heavy element with atomic number A ∿ 250.

Let us consider qualitatively the process of heating a compound target by electronic thermal conductivity. The time of inertial containment of a plasma with ionization multiplicity z, temperature T^z, and heavy-ion and DT-ion concentrations N^z and N^{DT}, respectively, is

$$\tau_u^z \approx \frac{A^*}{z^3}\tau_u^{DT}(T^{DT})\frac{N^{DT}}{N^z}\left(\frac{T^z}{T^{DT}}\right)^{3/2}, \quad (1)$$

where $\tau_u^{DT}(T^{DT})$ is the analogous time in a pure DT plasma with temperature T^{DT}, and $A^* = A/2.5$. Assuming the radiation pulse duration to be $\tau \simeq \tau_u^z$, let us find an expression for the depth of penetration of the thermal wave into the target

$$x^z_{fr} \approx x^{DT}_{fr}\frac{N^{DT}}{N^z}\left(\frac{T^z}{T^{DT}}\right)^2\frac{A^{*1/2}}{z^2}, \quad (2)$$

where x^{DT}_{fr} is the depth of heating in a pure DT plasma under the condition $\tau \simeq \tau_u^{DT}(T^{DT})$. Further, we have for the ratio of the energies E^z and E^{DT} per unit target surface area in both cases

$$\frac{E^z}{E^{DT}} = \frac{N^z z x^z_{fr} T^z}{N^{DT} x^{DT}_{fr} T^{DT}} = \left(\frac{T^z}{T^{DT}}\right)^3\frac{A^{*1/2}}{z}. \quad (3)$$

Assuming the diameter of the focusing spot to be $d \simeq 2x_{fr}$, we obtain the ratio of the total energies

$$\frac{W^z}{W^{DT}} = \frac{E^z}{E^{DT}}\left(\frac{x^z_{fr}}{x^{DT}_{fr}}\right) = \frac{A^{*3/2}}{z^5}\left(\frac{T^z}{T^{DT}}\right)^7\left(\frac{N^{DT}}{N^z}\right)^2. \quad (4)$$

The ratio of the neutron yields is then

$$\frac{N_n^z}{N_n^{DT}} = \frac{f(T^z)}{f(T^{DT})} \frac{\tau_u^z}{\tau_u^{DT}} \left(\frac{x_{fr}^z}{x_{fr}^{DT}}\right)^3 = \frac{A^{*5/2}}{z^9} \frac{f(T^z)}{f(T^{DT})} \left(\frac{N^{DT}}{N^z}\right)^4 \left(\frac{T^z}{T^{DT}}\right)^{15/2}, \quad (5)$$

where $f(T) = 10^{16}\langle\sigma v\rangle_{DT}$ is a function characterizing the rate of the DT reaction and varying from 1 to 15 when T changes from 10 keV to ∿50 keV. It follows from (4) that $T^Z = 20 - 30$ keV $> T^{DT} = 10$ keV can be obtained at energies $W^Z \simeq 10^3 - 10^4$ J ($A^* = 10^2$, $z = 50$). The corresponding neutron yield, as follows from (5), is $N_n^Z \simeq 10^{15}$. On the other hand, it should be noted that, from the point of view of obtaining an energywise-favored thermonuclear reaction, this method requires higher energies than with a pure DT plasma. However, since the rate of the DT reaction depends very strongly on T in the temperature region T ∿ 10 keV, the neutron yield in the pure DT mixture at energies 10^3 - 10^4 is smaller by many orders of magnitude than $N_n^Z \simeq 10^{15}$.

2. At sufficiently large radiation flux densities q(t), high values of the ionization multiplicity, $z \simeq 50$, can be attained within a time $\tau \simeq 10^{-10}$ sec as a result of non-equilibrium ionization [3]. The process of heating at $z \gg 1$ in the planar one-dimensional case (assuming that the target fills the half-space $x \leq 0$) can be described by the equation

$$\frac{\partial}{\partial T}[1.5 N^z z T] = \frac{\partial}{\partial x}\left[\kappa \frac{\partial T}{\partial x}\right] - Q_i, \quad (6)$$

$$\frac{\partial}{\partial t} z = \nu_i z,$$

where $\kappa = \kappa_0 \eta^{5/2} z^4$ is the coefficient of electronic thermal conductivity, $\eta = T/I(z)$, $I(z)$ is the ionization potential of an ion with multiplicity z ($I(z) = I_0 z^2$[3]), $\kappa_0 = 1.9\theta^{5/2} I_H^{5/2}/m^{1/2}e^4\Lambda$, $\theta = I_0/I_H$, $I_H = 13.6$ eV, Λ is the Coulomb logarithm, $\nu_i = (\nu_0/z^3)F(\eta)$ is the ionization probability of an ion of multiplicity z

$$F(\eta) = \eta^{1/2}\frac{\exp\{-\eta^{-1}\}}{1 + \chi\eta}, \quad \nu_0 = 2^{3/2}\theta^{-3/2} B N^z 10^{-8} \text{sec}^{-1}$$

(χ and B are slowly-varying functions of z [4]), and $\theta_i = (N_0 I_0/3)(\partial z^3/\partial t)$ is the rate of ionization loss per unit volume. The recombination processes, which were not taken into account in (6), impose a limit on the attainable ionization multiplicity, $z \lesssim z_0 \simeq 60$ [5]. The radiation of the plasma itself can also be neglected in comparison with the ionization loss, up to $z = z_0$. It is necessary to add to the system (6) the boundary condition

$$\kappa \frac{\partial T}{\partial x} = q(t) \quad \text{for } x = 0. \quad (7)$$

Equations (6) with the boundary condition (7) have an exact analytic solution if $T = z = 0$ for $t = 0$ and $q(t) \sim t$. The solution comprises heating and ionization waves in which fixed values of t and z move along the x axis with a velocity that is constant for all T and z. This velocity depends only on the parameters of the laser pulse and on the characteristics of the target material.

When $t = \tau_u^z$ and $x = 0$, this solution is best represented in the form

$$T = 3^{2/3}\eta(F\nu_o t)^{2/3}\theta l_H\left[1+\frac{x}{x_{fr}}\right]^{2/3} = \frac{48\eta^{8/3}\theta[FB_o A^*]^{2/3}}{\Lambda_o^{2/3}[4.5\eta+1]^{2/3}}\,\mathrm{keV},$$

$$z = [3F\nu_o t]^{1/3}\left[1+\frac{x}{x_{fr}}\right]^{1/3} = 60\eta^{5/6}[FB_o A^*]^{1/3}/\Lambda_o^{1/3}[4.5\eta+1]^{1/3},$$

$$x_{fr} = \eta^{7/4}\frac{[6F]^{1/2}}{[4.5\eta+1]^{1/2}}\nu_o \ell_o t = \frac{1.6\cdot 10^{-1}\eta^{7/4}\theta^2 A^*[B_o^{1/2}F^{1/2}]}{N_o^z\,\Lambda_o^{3/2}(4.5\eta+1)^{3/2}}\,\mathrm{cm},$$

$$\tau_o^z = \frac{2.4\,\theta^{3/2}\eta^{5/2}A^*}{N_o^z\Lambda_o[4.5\eta+1]}, \qquad (8)$$

$$W_o^z = \pi E_o^z x_{fr}^2 = \frac{9.7\cdot 10^{-1}B_o^{5/2}\theta^7\eta^{16}FA^*}{(N_o^z)^2\Lambda_o^{1/2}[4.5\eta+1]^{9/2}}\exp\left\{-\frac{3}{2\eta}\right\},$$

$$W_{out}/W^z = 10^{-4}k^2 f(T)\theta^{1/2}\exp\{1/\eta\}/B_o\eta^{1/2}[4.5\eta+1],$$

where E_0 is the laser-pulse energy per cm^2 of target surface, in units of 10^6 J/cm^2, τ_0^z is the pulse duration in units of 10^{-10} sec, N_0^z is the concentration of the heavy ions in units of 10^{21} cm^{-3}, $\Lambda_0 = \Lambda/10$, $B_0 = B/10$, W_{out} is the energy released in the thermonuclear reaction, and $k = N^{DT}/N_z$.

We note that $\tau_u^z \geq \tau^{e/z}$, where $\tau^{e/z}$ is the time of relaxation of the electrons with the heavy ions, and the temperature of the DT ions assumes under the conditions in question the temperature of the heavy ions, owing to the rapid exchange of energy between them. Be specifying the parameter η, we can determine with the aid of Formula (8) the plasma parameters and the values of E_0^z and τ_0^z, and W_0^z required for this purpose. We present numerical estimates, assuming that $N_0^z = 10$ ($N^z = 10^{22}$), $k = 10$, $B_0 = 1$, $\Lambda_0 = 1$, $A^* = 10^2$, and $\theta = 0.5$.

1. $W^z = 10^3$ J, $\tau^z = 10^{-10}$ sec, $T = 26$ keV, $x_{fr} = 2.3\cdot 10^{-3}$ cm,
   $W_{out}/W^z = 3.5\cdot 10^{-1}$, $N_n^z = 2\cdot 10^{14}$, $\eta = 0.7$.
2. $W^z = 8\cdot 10^3$ J, $\tau^z = 1.2\cdot 10^{-10}$ sec, $T = 37$ keV, $x_{fr} = 6\cdot 10^{-3}$ cm,
   $W_{out}/W_z = 2.5\cdot 10^{-1}$, $N_n^z = 10^{15}$, $\eta = 0.8$.

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PRODUCTION OF e^+e^- PAIRS IN AN ALTERNATING EXTERNAL FIELD

V.S. Popov
Institute of Theoretical and Experimental Physics, USSR Academy of Sciences
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Interaction of an electromagnetic field with a vacuum of charged particles leads to the appearance of nonlinear additions to the Lagrangian L of the electromagnetic field. In particular, there appears an imaginary part Im L, which determines the probability w of pair production by the external field. In the case of fields $\vec{E}$ and $\vec{H}$ constant in time (but alternating in space) it is possible to solve this problem exactly; this was done in [1] for scalar and spinor particles and in [2] for vector bosons with a gyromagnetic ratio g = 2. The following expression was obtained in these papers for the probability of pair production in a constant electric field E:

$$w = \frac{(2s+1)\alpha E^2}{4\pi^2} \sum_{n=1}^{\infty} \frac{\beta_n}{n^2} \exp\left(-\frac{n\pi m^2}{eE}\right). \tag{1}$$

Here $\hbar = c = 1$, $\alpha = e^2/\hbar c = 1/137$, s and m are the spin and mass of the particles produced by the field E, $\beta_n = (-1)^{n-1}$ for bosons, and $\beta_n = 1$ for fermions. The argument of the exponential in (1) is of the form nE_0/E, where $E_0 = \pi m^2 c^3/e\hbar = 4 \times 10^{16}$ V/cm (for electrons; since $E_0 \sim m^2$, the characteristic field intensity E_0 for other particles is even larger). We can therefore confine ourselves in the sum (1) to the first term with n = 1 for all the fields presently conceivable; this corresponds (as will be shown below) to the quasiclassical approximation.

We have obtained a generalization of (1) to the case of time-varying fields E(t). From the point of view of Dirac's theory, production of e^+e^- pairs corresponds to penetration of electrons with negative energy through a barrier of height $2mc^2$. In the quasiclassical approximation, the pair-production probability is

$$w \sim e^{-Q}, \qquad Q = 2\,\mathrm{Im}\,S \tag{2}$$

(accurate to the pre-exponential factor), where S is the action acquired by the particle as it moves along the under-the-barrier trajectory. Such a motion, which is impossible in classical mechanisms, can be regarded as occurring for pure imaginary values of the "time" t (cf. [3, 4], where this method was developed for ionization of atoms by an alternating electric field). To find the argument Q of the exponential, it suffices to find the extremal trajectory (that minimizes Im S), which in this case is one-dimensional. Using the equation of motion $\dot{p} = eE(t)$ and the expression $L = -m(1 - \dot{x}^2)^{1/2} + eE(t)x$, we can represent the action S in the form

$$S(t) = px - \int_{t_0}^{t} \sqrt{p^2 + m^2}\, dt$$

(for the case when the field E(t) is homogeneous in space and is directed along