Extremal physical conditions in thermonuclear combustion initiated by a laser beam

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An analysis is presented of the physical conditions that are produced in target plasma during the stage of thermonuclear combustion initiated by laser radiation.

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An analysis of the physical processes that occur during the stage of thermonuclear combustion in laser thermonuclear targets[1] offers evidence that it is possible to realize in the target plasma unique physical conditions never discussed previously. According to[1], at a laser-radiation initiating energy $E_{las} \lesssim 10^6$ J, in a target with DT fuel mass $M \gtrsim 10^{-3}$ g, the thermonuclear energy released is $E_{tn} \gtrsim 10^8$ J, which corresponds to the production of $\gtrsim 10^{19}$ neutrons (14 MeV) and an equal number of alpha particle (3.6 MeV). Let us estimate the characteristic values of the parameters of the thermonuclear plasma in the combustion process. At $M \approx 10^{-3}$ g, the initial values of the radius R_0 and of the density ρ_0 of the compressed nucleus, according to numerical calculations, amount to $R_0 \approx 10^{-2}$ cm and $\rho_0 \approx 2.5 \times 10^2$ g/cm^3, i.e., $\rho_0 R_0 \approx 2.5$ g/cm^2. In this case the alpha-particle mean free path is $l_\alpha \ll R_0 \approx 10^{-2}$ cm, i.e., all the produced alpha particles remain in the combustion region. The neutron range is $l_n \approx R_0 \approx 10^{-2}$ cm, and approximately 80% of the neutrons escape experiencing not more than one collision with the plasma ions. Consequently, the characteristic pressure is

$$P \approx \frac{0.4 E_{\text{tn}}}{{}^4\!/_3 \pi R_o^3} \approx 10^{20} \text{ erg/cm}^3 = 10^{14} \text{ atm}, \quad (1)$$

so that the combustion time determined by the hydrodynamic expansion τ_{hydr} is of the order of

$$\tau_{\text{hydr}} \approx \frac{R_o}{\sqrt{P/\rho}} \approx 2 \times 10^{-11} \text{ sec}. \quad (2)$$

The ion temperature $\bar{T}_i$ averaged over the volume is determined by the relation

$$P \approx n_i \bar{T}_i, \qquad n_i \approx 10^{26} \text{ cm}^{-3}, \qquad \bar{T}_i \approx 0.6 \text{ MeV} \quad (3)$$

and is connected with processes of energy transfer from the ions to alpha particles and neutrons, having characteristic times $\tau_{\alpha i} \approx \tau_{ni} \approx 10^{-11}$ sec.

On the other hand, inasmuch as the neutron-ion and ion-ion relaxation times ($T_i \approx 0.5$–1 MeV) also coincide in order of magnitude in our case with the lifetime $\tau_{\text{hydr}} \approx 10^{-11}$ sec of the thermonuclear plasma, one can expect a group of ions to exist with a temperature $T_i \gtrsim 1$ MeV, inasmuch as the energy transferred in one ion-neutron collision to the ion (D^+, T^+) is one 1—2 MeV. The number of hot ions $T_i \gtrsim 1$ MeV should then be approximately equal to the number of produced neutrons, $\sim 10^{19}$.

The characteristic densities of the neutrons (with energy 14 MeV) and of the alpha particles during the combustion time amount to $n_n \approx 10^{24}$ cm^{-3} and $n_\alpha \approx 10^{25}$ cm^{-3}. The neutron emission intensity is $\sim 10^{30}$ neut/sec. At this high neutron density, neutron-neutron scattering is possible with production of neutrons of energy ~ 29 MeV.

Time of combustion, sec.	$2 \cdot 10^{-11}$	–
ρ_o, g/cm^3	–	$4 \cdot 10^2$
R_o, cm	$1.4 \cdot 10^{-2}$	–
E_{tn}, J	–	$8.3 \cdot 10^7$
P, atm	$3 \cdot 10^{14}$	–
$\bar{T}_i$, keV	–	350
$\bar{T}_e$, keV	120	–
T_i^{max}, MeV	4	–
$N_n = N_\alpha$	$3 \cdot 10^{19}$	–
η_n	0.9	–

The foregoing estimates can be illustrated by the results of numerical calculations of thermonuclear combustion,[1] carried out with a program that takes into account, within the framework of two-temperature hydrodynamics, the processes of electron thermal conductivity, ion viscosity, volume radiation, and energy release as a result of the deceleration of alpha particles and neutrons. For the case $\rho_0 R_0 \approx 0.15$ g/cm^2, the model of local absorption of the alpha particles was used, and in the opposite case we used the model of volume energy release with allowance for the emission of the alpha particles.[2] The table lists the results of the calculation for a target with fuel mass $M = 6 \times 10^{-4}$ g at a laser-emission energy $E_{las} = 10^6$ J.

In the table, ρ_0 and R_0 are the initial (at the instant of the start of the flash) density and radius, $N_n = N_\alpha$ is the number of produced neutrons and alpha particles, T_i and T_e are the maximum temperatures during the combustion times, averaged over the mass, T_i^{max} is the maximum ion temperature, and η_n is the fraction of the emitted neutrons. Thus, the plasma obtained in the numerical experiment has during the stage of the thermonuclear combustion a number of unique parameters as follows: a pressure $\sim 10^{14}$ atm, much higher than is attainable under terrestrial conditions approximately 10^3 times the pressure in the central regions of the sun, a neutron-gas density $n_n \approx 10^{24}$ cm^{-3} and an alpha-particle density $n_\alpha \approx 10^{25}$ cm^{-3}, which are higher than the particle density in a solid in a normal state; "ultrahigh" ion and electron temperatures, $T_i \gtrsim 1$ MeV and $T_e \gtrsim 10^2$ keV, respectively; a neutron-radiation intensity $\sim 10^3$ neut/sec, making the target in question a unique pointlike source of neutrons, which can be used in various experiments. In principle, the plasma parameters obtained in the described numerical experiment can be registered in experiment by modern diagnostic means, for example, by using the ion, neutron, and x-ray spectra.

[1]Yu. V. Afanas'ev, N.G. Basov, P.P. Volosevich, E.G. Gamaliĭ, O.N. Krokhin, S.P. Kurdyumov, E.I. Levanov, V.B. Rozanov, A.A. Samarskiĭ, and A.N. Tikhonov, Pis'ma Zh. Eksp. Teor. Fiz. **21**, 150 (1975) [JETP Lett. **21**, 68 (1975)].

[2]O.N. Krokhin and V.B. Rozanov, in: Kvant. Elektron. (Moscow) No. 4, 118 (1972) [Sov. J. Quant. Electron. **2**, 393 (1973)].