

Possibility of determining the characteristics of laser plasma by measuring the neutrons of the DT reaction

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The characteristics of a laser plasma in a target of $(CD_2)_n$ can be determined by measuring the neutrons of the DT reaction. The ratio of the number of DT and DD neutrons produced in the plasma, and the spectrum of the DT neutrons, make it possible to determine the plasma temperature and density.

In recent experiments on plasma heating by a laser, carried out with a $(CD_2)_n$ target,^[1] there were registered besides the DD neutrons also DT neutrons produced in the reaction between the tritium and the deuterium of the plasma. The tritium is produced in one of the channels of the DD reaction, with initial velocity $v_0 \sim 8 \times 10^8$ cm/sec.

We investigate in this paper the connection between the characteristics of a laser plasma and the yield of the DT reaction and with the spectrum of the neutrons produced thereby.

It is known^[2,3] that spherical irradiation of a homogeneous target produces two regions with different physical parameters, a "corona" which is a region of "hot" ($T \sim 0.5-5$ keV) and relatively "tenuous" plasma ($n_D < 10^{22}$ cm⁻³) and a "compressed nucleus," which is a

region of dense plasma ($n_D > 10^{24}$ cm⁻³). If the temperature of the nucleus is high enough, ($T \geq 0.3$ keV), then the DD reaction can proceed effectively both in the corona and in the nucleus. It is of interest to point out the physical effects that could prove the presence of compressed and heated nucleus of the target. On the basis of these effects we can develop a diagnostic procedure for the superdense state of the plasma. As will be shown below, the neutrons from the DT reaction can serve as a good test of the presence of superdense target nucleus.

We consider two possible cases: a) the nucleus is compressed but is cold, $T_e < 0.1$ keV (the DD reaction occurs only in the corona); b) the nucleus is compressed and heated, $T_e > 0.3$ keV (the DD reaction occurs both in the corona and in the nucleus). The initial

quantity for the calculations in the spectral density $n(r, v)$ of the tritium nuclei, which have a velocity v . It is given by

$$n(r, v) = n_0(r, v) \exp \left[\int_v^{\infty} \frac{n_D \sigma(v)_{DT} v dv}{a(r, v)} \right]; \quad [n] = \frac{1}{[L]^3 [v]}, \quad (1)$$

where v is the tritium velocity, n_D is the deuterium density, $\sigma(v)_{DT}$ is the cross section of the DT reaction, $a(r, v) = dv/dl$ is the rate of slowing down of the tritium nuclei as they move in the plasma, and $n_0(r, v)$ is the spectral density of the tritium without allowance for its burning out as a result of the DT reaction. The principal effect that determines $n_0(r, v)$ is the deceleration of the tritium nuclei by the plasma electrons. If the spatial distribution of the tritium source, i.e., the rate of the DD reaction, is known, then the function $n_0(r, v)$ can be obtained by the procedure described in^[4], and in this case $\int_0^{\infty} n_0(r, v) dv$ turns out to be proportional to the number Q_{DD} of DD neutrons. We assume for simplicity that in the indicated cases (a) and (b) the source is homogeneous and, owing to the low density of the corona, the DT neutrons are produced only in the nucleus.

In the volume of the nucleus of radius r_0 , the number of Q_{DT} of the DT neutrons produced per unit time is

$$Q_{DT} = 4\pi \int_0^{r_0} \int_0^{\infty} n(r, v) n_D \sigma(v)_{DT} v dv r^2 dr. \quad (2)$$

The deuterium nuclei are assumed to be at rest. The energy spectrum of the DT neutrons is given by

$$\frac{dQ_{DT}}{dE_n} = 4\pi \int_0^{r_0} \int_0^{\infty} n(r, v) n_D \sigma(v)_{DT} v F(u) v dv r^2 dr, \quad (3)$$

where $F(u)$ is the probability of emitting, via the DT reaction, a neutron with velocity u in a unit energy interval in the laboratory frames; E_n is the neutron energy in the l.s., and $F(u)$ takes the form^[5]:

$$F(u) = \begin{cases} \frac{1}{2m_n v_c u_c} & \text{if } u_c - v_c < u < u_c + v_c \\ 0 & \text{if } u_c + v_c < u \text{ and } u < u_c - v_c \end{cases}$$

here

$$u_c = \left[u_0^2 + \frac{m_T m_D m_\alpha}{(m_T + m_D)(m_n + m_\alpha) m_n} v^2 \right]^{1/2}$$

is the velocity of the DT neutron in the c.m.s.; $v_c = vm_T/(m_T + m_D)$ is the velocity of the mass center; u_0 is the velocity of the neutron produced as a result of the reaction of the immobile tritium and deuterium nuclei ($v=0$); m_T , m_D , m_n , and m_α are respectively the masses of the tritium, deuterium, neutron, and α particle.

Omitting the intermediate steps, we present the calculated ratio of the number of DT and DD neutrons (Q_{DT}/Q_{DD}), and also the spectrum of the DT neutrons, for the two cases indicated above. We used in the calculations the data on the cross sections of the DT and DD reactions from^[6],

a) Cold target nucleus; then

$$\frac{Q_{DT}}{Q_{DD}} = \frac{3}{2} \delta^2 \left[\frac{n_D \bar{\sigma}_{DT} \lambda_1 \left(\frac{1}{4r_1} \right)}{1 + \delta + \delta^2} \right], \quad (4)$$

where $\delta = r_0/R$; $\tau_1 = r_0/\lambda_1$; r_0 is the target-nucleus radius, R is the radius of the entire target; $\lambda_1 = 6.84 \times 10^{19}/n_e$ cm is the slowing-down length of the tritium in the "cold" nucleus; $\bar{\sigma}_{DT} = 10^{-24}$ cm²; n_D is the density of the deuterium nuclei in the nucleus; n_e is density of the electrons in the nucleus.

b) The target nucleus is hot; in this case we have the following: 1) If $\tau_2 = r_0/\lambda_2 \leq 3/16$ (the target nucleus is partially transparent to the tritium nuclei), then

$$\frac{Q_{DT}}{Q_{DD}} = n_D \sigma(v_0)_{DT} r_0 (1 + 61.2 \tau_2^2) \quad (5)$$

here $\lambda_2 = 3.36 \times 10^{21} T_e^{3/2}/n_e$ cm is the slowing-down length of the tritium in the "hot" nucleus; $\sigma(v_0)_{DT} = 1.5 \times 10^{-25}$ cm², and T_e is the temperature of the electrons in the nucleus in keV.

2) If $\tau_2 \geq 4$ (the tritium nuclei are strongly slowed down and hardly ever leave the nucleus), then

$$\frac{Q_{DT}}{Q_{DD}} = n_D \sigma_{DT} \lambda_2 \left(1 - \frac{3}{2\tau_2} \right) \sim T_e^{3/2}, \quad (6)$$

where

$$\sigma_{DT} = 1.54 \cdot 10^{-24} \text{ cm}^2.$$

Figure 1 shows plots of the ratio Q_{DT}/Q_{DD} against the electron temperature T_e in the target nucleus, at various deuterium densities n_D in the nucleus; the temperature and density of the corona are respectively 1 keV and 10^{22} cm⁻³, while $r_0/R \sim 0.3$. It is seen from these calculations that under the experimental conditions of^[11] (cold nucleus) the ratio Q_{DT}/Q_{DD} amounts to $\sim 10^{-5}$, and at a laser-radiation energy 300 J (hot nucleus) the ratio Q_{DT}/Q_{DD} is approximately 10^{-3} .

Figure 2 shows the spectra of the DT neutrons for a "hot" nucleus and for $\lambda_2 \ll r_0$ and $\lambda_0 = 5r_0$. In the case of the "cold" nucleus, the spectrum coincides with that

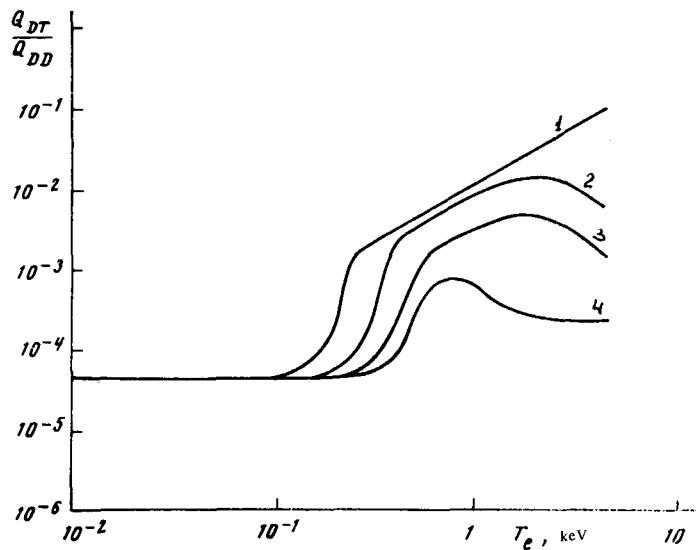


FIG. 1. The ratio Q_{DT}/Q_{DD} vs. the electron temperature (T_e) in the target nucleus: curves 1, 2, 3, and 4 correspond to the deuterium densities in the target nucleus 10^{25} , 10^{24} , 5×10^{23} , and 10^{23} cm⁻³.

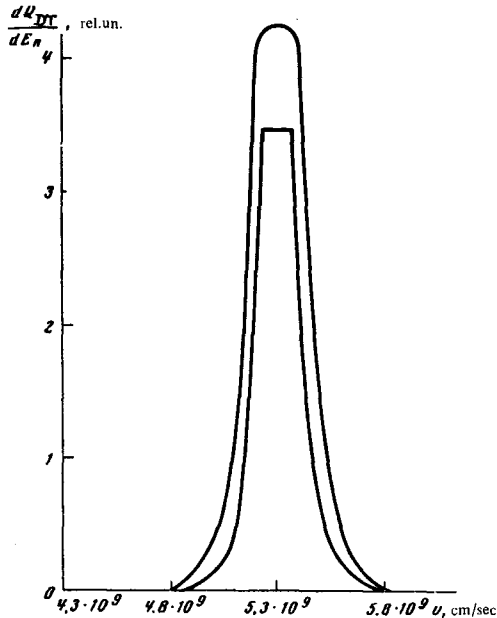


FIG. 2. Spectra of DT neutrons: 1) $\tau_2 \gg 1$; 2) $\tau_2 = 0.2$.

shown in Fig. 2 for $\lambda_2 \ll r_0$. The spectra are practically symmetrical with respect to the neutron velocity $u_0 \approx 5.3 \times 10^9$ cm/sec, and their width is of the order of $\Delta u = m_T v_0 / (m_T + m_D) \approx 4.8 \times 10^8$ cm/sec ($\Delta E_n = 2.6$ meV). The spectrum of the DD neutrons has a Gaussian form of width $\Delta u \approx 8 \times 10^7$ cm/sec ($\Delta E_n = 0.14$ meV) at an ion temperature in the plasma $T_i = 3$ keV. The width δu of the horizontal section in the spectrum, which appears when $\lambda_2 > 4r_0$, is

$$\delta u = \frac{2m_T}{m_T + m_D} v_0 = \frac{2m_T}{m_T + m_D} \left(v_0 - \frac{4.76 \cdot 10^{-13} n_e 4r_0}{T_e^{3/2}} \right). \quad (7)$$

The presence of this horizontal section is due to the fact that the plasma does not contain tritium nuclei with velocities $v < v_*$, all of which escape the plasma.

Thus, a symptom of a "hot" nucleus is a higher value of the ratio Q_{DT}/Q_{DD} (on the order of 10^{-3}), and also (if the nucleus is partially transparent to the tritium) the presence of a horizontal section in the neutron spectrum. The temperature and density of the compressed target nucleus can be determined from measurements of Q_{DD} and Q_{DT}/Q_{DD} with the aid of relations (5) and (7).

We note in conclusion that consideration of the temporal evolution of the laser plasma shows that the largest yield of the DT neutrons is obtained at instants of time closest to the instant of maximum compression of the target nucleus, and therefore in all the relations presented here the temperature, density, and radius of the target nucleus coincide with the corresponding values for the instant of maximum compression.

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