Energy transport by recoil nuclei in the scattering of fusion neutrons in a dense bounded plasma

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The fraction of the energy which is transferred to the deuterium-tritium plasma of spherical laser targets by the recoil nuclei formed in the elastic scattering of fusion neutrons is determined. This energy transport by recoil nuclei is shown to determine the nature of the energy transfer of the fusion neutrons to a significant extent.

An important topic in the theory of the fusion burning of a dense, inhomogeneous plasma is the problem of the energy transport by fusion particles, i.e., the products of fusion reactions. If the reactions are initially started in a plasma region with dimensions comparable to the stopping lengths of the fusion particles in it, the transport by these particles of the energy which is released may lead to a self-sustaining fusion-reaction wave.[1,2] The attainment of such a highly efficient reaction in a plasma which is bounded with respect to the ranges of the fusion particles, formed upon the compression of a spherical target, is the basic concept of inertial-confinement fusion, in particular, laser fusion.[1]

Fusion particles with initial energies of a few MeV constitute a group of high-energy particles with respect to the ions and electrons of the fusion plasma, with a temperature $T_{e,i} = 10$–100 keV.

The charged particles transfer their energy to electrons and ions of the plasma through the Coulomb interaction. Since this is a long-range interaction, the energy transferred in each collision event is small—much smaller than the energy of a particle.[3]

A different type of energy transfer occurs in the elastic scattering of neutrons by plasma ions. The classical theory (e.g., Ref. 4) tells us that in an elastic scattering a neutron with an initial energy E_{n0} can transfer to a nucleus at rest an energy in the range from 0 to $E_{jm} = 4A_j E_{n0}/(A_j + 1)^2$ with equal probabilities (A_j is the ratio of the mass of the nucleus, m_j, to that of the neutron, m_n).

It follows that in the scattering of fusion neutrons from the DT reaction with $E_{n0} \simeq 14.1$ MeV by light nuclei in a deuterium-tritium plasma the energy is transferred to recoil nuclei, most of which acquire an energy of a few MeV (for deuterium recoil nuclei, we have $E_{dm} = 12.5$ MeV, and for tritium we have $E_{tm} = 10.5$ MeV).

The stopping length of a particle in the case of Coulomb stopping in a dense plasma depends on the charge, mass, and energy of the particle. These parameters are approximately the same for the light recoil nuclei in a deuterium-tritium plasma and the fusion particles, so that the recoil nuclei, like the charged fusion particles, represent a group of high-energy particles with stopping lengths comparable to the dimensions of the plasma in a laser-fusion target.

Afanas'ev *et al.*[5] have called attention to the possible formation of recoil nuclei with energies of several MeV during a laser microexplosion, but they did not take up the energy transport by these nuclei.

In the present paper we estimate the effect of the energy transport by recoil nuclei, and we demonstrate the need for calculations at the kinetic level of this second stage of the transfer of energy to the plasma from fusion neutrons.

1. We consider the transport of energy by the recoil nuclei which are formed in a homogeneous, spherically symmetric plasma of radius R. For this purpose, we find the fraction of the energy which is transferred to the plasma by the recoil nuclei as a function of the ratio of the plasma radius to the scale stopping length of the particles.

For the calculations it is convenient to use the results found in Refs. 6 and 7 regarding the transport of energy by charged fusion particles, since the latter have the same properties of motion in a dense plasma as the light recoil nuclei, as we stated above. The most important of these properties, which apply to reaction-initiation temperatures 1 keV$\leqslant T \leqslant$20 keV in a plasma, are the predominant stopping of particles by electrons and the relative unimportance of scattering by plasma ions.

The reason is that the rate of Coulomb collisions of a particle with plasma electrons is considerably larger than the rate of collisions with ions (in this temperature range).

The fusion particles start with a velocity spectrum lumped in a single line; the ratio of the width of this spectrum to the initial velocity is $(T_i/E_{c0})^{1/2}$ in order of magnitude, where E_{c0} is the initial energy of the particles.

Gus'kov[6,7] solved the kinetic equation under the approximations outlined above for the fraction of the energy transferred by fusion particles to a homogeneous, spherically symmetric plasma of radius R, finding

$$\frac{W_{cp}}{W_{cf}} = \begin{cases} \dfrac{3}{2}\tau_c - \dfrac{4}{5}\tau_c^2 , & \tau_c = \dfrac{R}{\lambda_c} \leqslant \dfrac{1}{2} \\ 1 - \dfrac{1}{4\tau_c} + \dfrac{1}{160\tau_c^3} , & \tau_c \geqslant \dfrac{1}{2} \end{cases} . \qquad (1)$$

Here $W_{cf} = E_{c0}\dot{N}_c$ is the total energy of the fusion particles which are produced per unit time in the plasma; W_{cf} is the energy of the particles which is transferred to the plasma; $\dot{N}_c$ is the strength of the source of particles; and λ_c is the stopping length of a particle undergoing Coulomb interactions with electrons, given by

$$\lambda_c = \frac{3T_e^{3/2}}{8\sqrt{\pi}L(e_c e)^2 m_e^{1/2} n_e} v_{c0} . \tag{2}$$

Here m_c, e_c, and v_{c0} are, respectively, the mass, charge, and initial velocity of the particle; m_e and e are the mass and charge of the electron; and n_e is the electron density.[6] For α particles with an initial velocity $v_{\alpha 0} \simeq 1.3\times 10^9$ cm/s in a DT plasma we would have

$$\lambda_\alpha \simeq 1.08\times 10^{-1} T_e^{3/2} / \rho L ,$$

where $L \simeq 7-10$ is the Coulomb logarithm, and ρ is the mass density of the plasma. The recoil nuclei, in contrast with the fusion particles, have an initial velocity spectrum which is stretched out and linear in the velocity. Using the approximation that the formation of recoil nuclei with energies in the interval from 0 to E_{jm} is equiprobable, we find

$$\frac{\partial N_j}{\partial v_{j0}} = \dot{N}_s m_j v_{j0} E_{jm}^{-1} , \tag{3}$$

where $\dot{N}_S$ is the number of events per unit time in which a fusion neutron is scattered elastically by a plasma ion.

For a monovelocity spectrum, the ratio W_{cp}/W_{cf} depends on the initial velocity of the particles through the stopping length, $\tau_c \sim \lambda_c^{-1} \sim v_{c0}^{-1}$ [see Eqs. (1) and (2)]. Taking an average of (1) over spectrum (3), we find the result we were seeking:

$$\frac{W_{jp}}{W_{jf}} = \begin{cases} 3\tau_{jm} - \dfrac{244}{75}\tau_{jm}^2 + \dfrac{8}{5}\tau_{jm}^2 \ln 2\tau_{jm} , & \tau_{jm} = \dfrac{R}{\lambda_n} \leqslant \dfrac{1}{2} \\ 1 - \dfrac{1}{6\tau_{jm}} + \dfrac{1}{400\tau_{jm}^3} , & \tau_{jm} \geqslant \dfrac{1}{2} , \end{cases} \tag{4}$$

where $W_{jf} = \frac{1}{2} E_{jm} \dot{N}_S$ is the energy of the recoil nuclei, and λ_{jm} is the stopping length of the recoil nuclei with $v_{j0} = v_{jm}$. Using (2), we find $\lambda_{dm} \simeq 5.3\,\lambda_\alpha$, $\lambda_{tm} \simeq 6.2\,\lambda_\alpha$.

For $\lambda_n > R$ we have $\dot{N}_S \sim R/\lambda_n$; according to Ref. 7, we have $\dot{N}_S \simeq \dot{N}_n \frac{4\pi R^3}{3} \frac{3}{4} \frac{R}{\lambda_n}$, where $\lambda_n = \frac{4}{\rho}$ cm (Ref. 8).

2. *Conclusion.* The calculated results shown in Fig. 1 demonstrate that the plasma of a laser-fusion target is more transparent for deuterium and tritium recoil nuclei than for α particles. The explanation is that, despite the extended spectrum, most of the recoil nuclei have initial energies above the energy of the α particles. Furthermore, their charge is half that of the α particles.

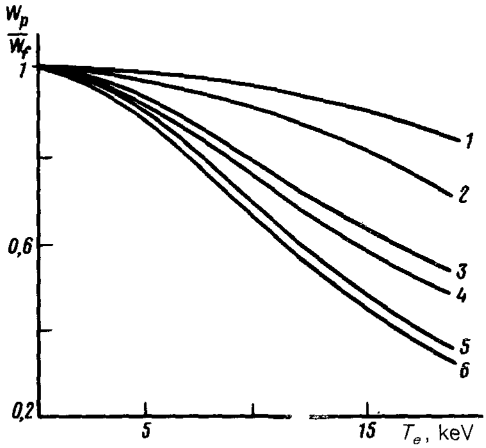

FIG. 1. 1,2—$W_{\alpha p}/W_{\alpha f}$; 3,5—$W_{dp}/W_{df}$; 4,6—$W_{tp}/W_{tf}$ versus the temperature T_e. 1,3,4—$\rho R = 1.4$ g/cm^2; 2,5,6—$\rho R = 0.83$ g/cm^2.

The data in Fig. 2 show that in a dense plasma with $\rho R \geqslant 1$, in which the efficiency of the scattering of fusion neutrons is high, the recoil nuclei contribute substantially to the transport of the fusion energy that is released. In this case, essentially all α particles remain in the burning region, and the transport of energy by the recoil nuclei turns out to be the dominant mechanisms for the propagation of the fusion-reaction wave.

In summary, the transfer of energy from the fusion neutrons in the plasma of a laser-fusion target cannot be regarded as a local process, occurring at the same point at which the elastic scattering occurred. The actual picture of the heating of a target by fusion neutrons can be seen only by taking into account the energy transport by recoil nuclei.

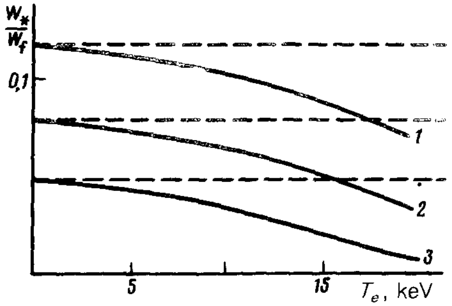

FIG. 2. The ratio W_*/W_f, the fraction of the fusion-reaction energy which is transferred to the plasma by recoil nuclei, versus the temperature T_e. The dashed lines show W_n/W_f without consideration of the energy transport by recoil nuclei. 1,2,3—$\rho R = 2.1$, 1.4, and 0.83 g/cm^2.

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