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Yongtao Zhao, Dieter Hoffmann

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Equation of state for non-isothermal dense hydrogen plasma in ICF

M.T. Gabdullin†[1], T.S.Ramazanov*[2], Zh.A. Moldabekov*[3], T.N.Ismagambetova*[4] and G.B.Akhtanova*[5]

†Al-Farabi Kazakh National University, NNLOT, 71 al-Farabi Av., Almaty 050040, Kazakhstan
*Al-Farabi Kazakh National University, IETP, 71 al-Farabi Av., Almaty 050040, Kazakhstan

In this work a partially ionized plasma under extreme conditions which is in such experiments using heavy ion beams have been investigated. Particularly, equation of state and shock adiabatic (hugoniot) which connects the density and pressure of the plasma ahead and behind of the shock wave are calculated.

The effective screened interaction potentials [1,2] for nonideal dense electron-ion plasma which taking into account electron's wave nature at small interparticle distances is used:

$$\Phi_{\alpha\beta}(r)=\frac{Z_\alpha Z_\beta e^2}{r}\frac{1}{\gamma^2\sqrt{1-\left(2k_D/\lambda_{ee}\gamma^2\right)^2}}\times$$
$$\left(\left(\frac{1/\lambda_{ee}^2-B^2}{1-B^2\lambda_{\alpha\beta}^2}\right)\exp(-Br)-\left(\frac{1/\lambda_{ee}^2-A^2}{1-A^2\lambda_{\alpha\beta}^2}\right)\exp(-Ar)\right)-$$
$$-\frac{Z_\alpha Z_\beta e^2}{r}\frac{(1-\delta_{\alpha\beta})}{1+C_{\alpha\beta}}\exp(-r/\lambda_{\alpha\beta}), \quad (1)$$

where

$$A^2=\frac{\gamma^2}{2}\left(1+\sqrt{1-\left(\frac{2k_D}{\lambda_{ee}\gamma^2}\right)^2}\right),\quad B^2=\frac{\gamma^2}{2}\left(1-\sqrt{1-\left(\frac{2k_D}{\lambda_{ee}\gamma^2}\right)^2}\right),$$

$$C_{\alpha\beta}=\frac{k_D^2\lambda_{\alpha\beta}^2-k_i^2\lambda_{ee}^2}{\lambda_{ae}^2/\lambda_{\alpha\beta}^2-1},$$

and $\gamma^2=k_i^2+1/\lambda_{ee}^2$, $k_D^2=k_e^2+k_i^2$ is screening parameter, $\lambda_{\alpha\beta}=\hbar/\sqrt{4\pi\, m_{\alpha\beta}k_B T_{\alpha\beta}}$ is thermal wave length.

The effective potentials (1) can be used for non-isothermal as well as for isothermal plasmas. The electron-ion temperature of non-isothermal plasmas is presented as $T_{ei}=\sqrt{T_eT_i}$ [3].

Equation of state for dense hydrogen plasma is calculated by shock wave compression hydrogen modeling. In presented approach the analytical expression of the correlation energy and excess part of the pressure are calculated on the basis of effective potentials (1). The correlation energy has the following form:

$$U_N=-2\pi V\sum_{\alpha,\beta}\frac{n_\alpha, n_\beta\, e_\alpha^2 e_\beta^2}{k_B T_{\alpha\beta}\gamma^2\sqrt{1-\left(2k_D/\lambda_{ee}\gamma^2\right)^2}}\times$$
$$\times\left[\frac{1/\lambda_{ee}^2-B^2}{B\left(1-B^2\lambda_{\alpha\beta}^2\right)\left(1+B\lambda_{\alpha\beta}\right)}-\frac{1/\lambda_{ee}^2-A^2}{A\left(1-A^2\lambda_{\alpha\beta}^2\right)\left(1+A\lambda_{\alpha\beta}\right)}\right]+$$
$$+2\pi Ve^2\left(2Z_in_in_e\lambda_{ei}^2-n_e^2\lambda_{ee}^2+\frac{Z_in_in_e\lambda_{ei}e^2}{k_BT_{ei}(1-C_{ei})}\right). \quad (2)$$

Equation of state has the form:

$$P=P_{id}-\frac{2\pi}{3}\sum_{\alpha,\beta}\frac{n_\alpha, n_\beta\, e_\alpha^2 e_\beta^2}{k_B T_{\alpha\beta}\gamma^2\sqrt{1-\left(2k_D/\lambda_{ee}\gamma^2\right)^2}}\times$$
$$\times\left[\frac{1/\lambda_{ee}^2-B^2}{B\left(1-B^2\lambda_{\alpha\beta}^2\right)\left(1+B\lambda_{\alpha\beta}\right)^2}-\frac{1/\lambda_{ee}^2-A^2}{A\left(1-A^2\lambda_{\alpha\beta}^2\right)\left(1+A\lambda_{\alpha\beta}\right)^2}\right]+$$
$$+2\pi e^2\left(2Z_in_in_e\lambda_{ei}^2-n_e^2\lambda_{ee}^2+\frac{Z_in_in_e\lambda_{ei}e^2}{12k_BT_{ei}(1-C_{ei})}\right). \quad (3)$$

Ionization degree is calculated using modified Saha equation with lowering of ionization potential hydrogen atoms.

Additionally, calculation of shock adiabatic in HNC approximation using Deutsch quantum potential [4] and Saha equation is done.

Obtained results are compared with experimental data [5] on shock wave experiments and with other known theoretical approaches.

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[1]E-mail: gabdullin@physics.kz
[2]E-mail: ramazan@physics.kz
[3]E-mail: zhandos@physics.kz
[4]E-mail: miriael@mail.ru
[5]E-mail: g.akhtanova@gmail.com

Stopping power and relaxation processes of a dense plasma in inertial confinement fusion

Issanova M.K.*[1], Ramazanov T.S.*[2], Kodanova S.K.*[3], Moldabekov Zh.A.*[4], Hoffmann D.H.H. †[5]

* IETP, Al-Farabi Kazakh National University, Almaty 050040, Kazakhstan
† Institute of Nuclear Physics, TUD, Darmstadt, 64289, Germany

Nowadays, a state of matter under extremely high pressure is an object of high interest. Investigation of dense matter has crucial importance for application [1] as well as for understanding of universe evolution. Particularly, many expectations associated with an inertial confinement fusion, where dense plasma is a working substance. Experimental investigation of dense nonideal plasmas based on using of a shock wave compression, a high-power laser and an ion accelerator devices [1-2]. A characteristic feature of all of the above experiments is that the resulting plasma is non-isothermal. The reason for that is a big difference between the mass of ion and electron.

In presented work stopping power of the projectile ions in a dense, non-isothermal plasma and temperature relaxation between electrons and ions are considered. These properties of plasma have to be calculated accurately taking into account both quantum and collective effects in plasmas.

The stopping power for protons in a dense plasma represented as the sum of contributions due to bound electrons (be) and free plasma electrons (fe) [3].

$$-\frac{dE}{dx}=\frac{4\pi e^4 n_{fe} Z_{eff}^2}{m_e \upsilon_p^2}\left(\lambda_{fe}+\sum_k \frac{n_k}{n_{fe}}\nu_{hk}\lambda_{be}\right), \quad (1)$$

where υ_p and Z_{eff} are the velocity and the effective charge of the ion, n_k is the number density of the ion species k, ν_{hk} is the number of bound electrons in the ion k; λ_{fe} and λ_{be} are the Coulomb logarithms for the free and bound electrons, respectively.

The Coulomb logarithm is obtained on the basis of effective potentials. These interaction potentials take into consideration long-range many particle screening effects as well as short-range quantum-mechanical effects[4-6].

The Coulomb logarithm is determined by the center-of mass scattering angle θ_c [7]:

$$\lambda_{\alpha\beta}=\frac{1}{b_\perp^2}\int_0^{b_{max}}\sin^2\left(\frac{\theta_c}{2}\right) b\, db, \quad (2)$$

$$\theta_c=\pi-2b\int_{r_0}^{\infty}\frac{dr}{r^2}\left(1-\frac{V(r)}{E_c}-\frac{b^2}{r^2}\right)^{-1/2}, \quad (3)$$

where $E_c=\frac{1}{2}m_{\alpha\beta}\upsilon^2$, $m_{\alpha\beta}=m_\alpha m_\beta/(m_\alpha+m_\beta)$ is the reduced mass of the particles of species α and β, $V(r)$ is the interaction potential of particles, r_0 is the classical distance of the closest approach, $b_\perp=Z_\alpha Z_\beta/(m_{\alpha\beta}\upsilon^2)$ is the impact parameter for 90^0 scattering. We take the maximum and minimum impact parameters as $b_{max}=r_D$, $b_{min}=\max\{b_\perp,\lambda_{\alpha\beta}\}$, where r_D is the Debye radius, $\lambda\!\!\!^{-}_{\alpha\beta}$ is de Broglie wavelength.

Relaxation of temperatures is investigated in a wide range of plasma parameters according to well known formula

$$\frac{dT_\alpha}{dt}=\frac{T_\alpha-T_\beta}{\tau_{\alpha\beta}}, \quad (4)$$

here

$$\tau_{\alpha\beta}=\frac{1}{\nu_{\alpha\beta}}=\frac{3m_\alpha m_\beta}{8\sqrt{2\pi}n_\beta e^4\lambda_{\alpha\beta}}\left(\frac{k_B T_\alpha}{m_\alpha}\right)^{3/2}. \quad (5)$$

Obtained results for stopping power and relaxation time compared with an available experimental data [8] and molecular-dynamics simulation results [9]. Also, advantages and disadvantages of used approach in comparison with other theoretical methods are discussed.

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[1] E-mail: isanova_moldir@mail.ru
[2] E-mail: ramazan@physics.kz
[3] E-mail: kodanova@mail.ru
[4] E-mail: zhandos@physics.kz
[5] E-mail: hoffmann@physik.tu-darmstadt.de