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Relaxation of composition and species temperatures in laser- and shock-produced plasmas

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Abstract

We investigate the coupled relaxation of plasma composition and species temperatures in dense two-temperature plasmas. Nonideality effects are included in the rate coefficients of impact ionization and by quasi-particle shifts that modify the charge carrier energies. Results are presented for laser-produced and for shock-produced plasmas which have very different initial conditions for the species temperatures.

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1. Introduction

The coupled relaxation of plasma composition and species temperatures is of interest in many experiments that rapidly couple energy into matter. Laser and particle beams, for instance, not only produce plasmas with hot electrons and colder ions, but they also create systems with enhanced ionization degrees (e.g. due to field ionization or additional high energy impacts). The opposite temperature relation is found in shocked matter. However, the evolution of plasma composition and the energy transfer between electrons and ions strongly influence each other in both cases.

Recent laser and shock experiments [1–3] found strong hints of a much slower relaxation in dense plasmas than the usual Landau–Spitzer theory [4, 5] predicts. Complementing these findings, theoretical efforts studied the influence of collective electron–ion modes [6, 7], strong electron–ion collisions [8, 9] and equation of state effects on the relaxation [10]. Additionally, dense plasma effects on the ionization kinetics at fixed temperature have been investigated intensively [11, 12]. Balance equations for the coupled relaxation of plasma composition and species temperatures were derived and evaluated in [13–15] on the basis of quantum kinetic equations for reacting, nonideal systems [16]. Here, we start from the energy conservation condition which allows a more general treatment of the correlation energy.

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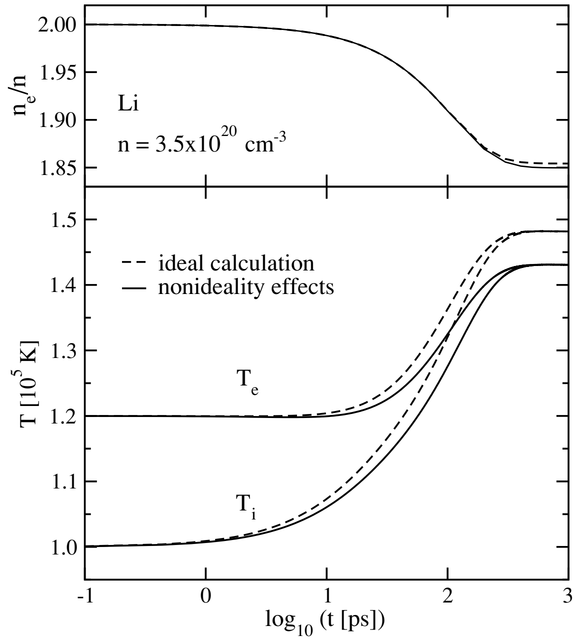

Figure 1. Evolution of the ionization degree and the species temperatures for a lithium plasma with a density of the heavy particles of $n = 3.5 \times 10^{20}\ \mathrm{cm}^{-3}$. The results for a nonideal plasma with quasi-particle shifts on the Debye level are compared with those for the model of an ideal plasma.

2. Energy transfer rates and ionization kinetics

The electron–ion energy transfer rate and the ionization/recombination rates are the main ingredients that determine the coupled relaxation towards equilibrium. Since the focus is here on the complex interplay between the two processes, we restrict ourselves to rather simple expressions for these rates. In the fast and easy-to-use Landau–Spitzer approach, the rate of energy transfer between electrons and ions with charge Z_i is given by [5]

$$Z_\mathrm{ei}^\mathrm{LS} = \frac{3n_\mathrm{e}k_\mathrm{B}}{2}\frac{T_\mathrm{i}-T_\mathrm{e}}{\tau_\mathrm{ei}} \qquad \text{with} \qquad \tau_\mathrm{ei} = \frac{3m_\mathrm{e}m_\mathrm{i}}{8\sqrt{2\pi}n_\mathrm{i}Z_\mathrm{i}^2e^4\ln\Lambda}\left(\frac{k_\mathrm{B}T_\mathrm{e}}{m_\mathrm{e}}+\frac{k_\mathrm{B}T_\mathrm{i}}{m_\mathrm{i}}\right)^{3/2}. \tag{1}$$

Here, $\ln\Lambda$ denotes the Coulomb logarithm. To allow for strong collisions, we use the form that considers hyperbolic orbits and approximately includes quantum effects [9]

$$\ln\Lambda = \frac{1}{2}\ln\left(1+\frac{\lambda_D^2}{\varrho_\perp^2+\lambda_\mathrm{dB}^2}\right) \qquad \text{with} \qquad \begin{array}{l}\lambda_\mathrm{D} = (k_\mathrm{B}T_\mathrm{e}/4\pi e^2n_\mathrm{e})^{1/2},\\ \varrho_\perp = Z_\mathrm{i}e^2/m_\mathrm{e}v_\mathrm{th}^2,\ \lambda_\mathrm{dB} = \hbar/m_\mathrm{e}v_\mathrm{th},\end{array} \tag{2}$$

where $v_\mathrm{th} = \sqrt{k_\mathrm{B}T_\mathrm{e}/m_\mathrm{e}}$ denotes the thermal velocity of the electrons. All heavy particles are described by a common temperature T_i.

The evolution of the plasma composition is calculated by the following system of rate equations, where only electron impact ionization is considered:

$$\begin{aligned}\dot n_0 &= n_\mathrm{e}n_\mathrm{e}n_1\beta_0 - n_\mathrm{e}n_0\alpha_0\\ \dot n_1 &= n_\mathrm{e}n_\mathrm{e}n_2\beta_1 - n_\mathrm{e}n_1\alpha_1 - n_\mathrm{e}n_\mathrm{e}n_1\beta_0 + n_\mathrm{e}n_0\alpha_0\\ &\vdots\\ \dot n_{Z-1} &= n_\mathrm{e}n_\mathrm{e}n_Z\beta_{Z-1} - n_\mathrm{e}n_{Z-1}\alpha_{Z-1} - n_\mathrm{e}n_\mathrm{e}n_{Z-1}\beta_{Z-2} + n_\mathrm{e}n_{Z-2}\alpha_{Z-2}.\end{aligned} \tag{3}$$

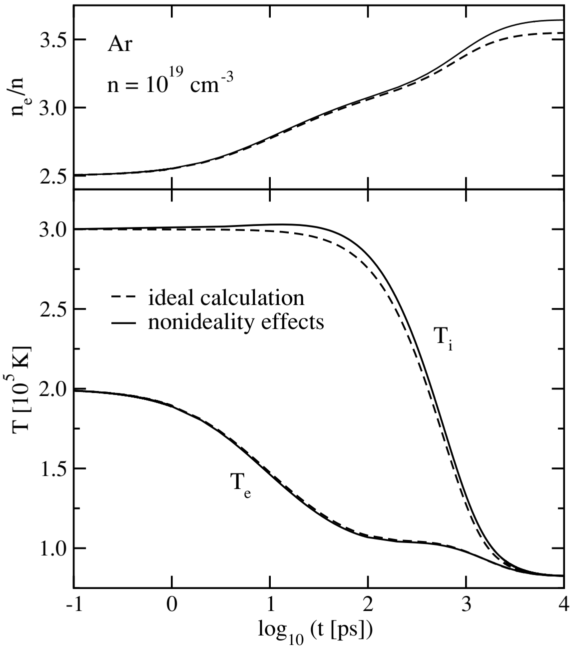

Figure 2. Temporal behaviour of the ionization degree and the species temperatures for a shock-produced argon plasma with a heavy particle density of $n = 10^{19}$ cm^{-3} and an ionization degree of 2.5. The results for a nonideal plasma with quasi-particle shifts on the Debye level are compared with those for the model of an ideal plasma.

The evolution of the electron density is determined by quasi-neutrality. Here and in the following, we omit excited states since we want to focus on nonideality effects; the excited states can be easily included as is done in ideal systems.

Nonideality effects in the coefficient of impact ionization are included in the form $\alpha_i = \alpha_i^{\mathrm{id}} \exp(\Delta_{i+1} - \Delta_i + \Delta_\mathrm{e})$ [11], whereas the recombination coefficient β_i is unchanged from its ideal form. The quasi-particle shifts Δ describe approximately the effects of the surrounding plasma on the one-particle energies. In the Debye approximation, we have $\Delta_i = -\left(Z_\mathrm{i}^2 e^2 \kappa\right)/2$ with κ being the inverse Debye screening length. The ideal rate coefficients α_i^{id} and β_i^{id} are calculated from Seaton's fit formula [17].

3. Coupled density–temperature relaxation

The coupled density–temperature relaxation is determined by the conservation of the total energy density given here for a weakly coupled, classical plasma [18]

$$\varepsilon = \sum_a \left(\frac{3}{2} n_a k_\mathrm{B} T_a + n_a \Delta_a \right) + E^{\mathrm{bound}}, \tag{4}$$

where the sum runs over electrons and all ionization stages. E^{bound} denotes the density of total binding energy which we assign to the energy density of the electron system. The energy content of both subsystems, electrons and heavy particles, is only changed by the electron–ion energy transfer rate. We therefore find

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_e k_B T_e + n_e \Delta_e\right) = Z_{ei}(T_e, T_i) - \sum_{i=1}^{Z} E_i W^{i\to i-1} \qquad (5)$$

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n k_B T_i + \sum_{i=1}^{Z} n_i \Delta_i\right) = -Z_{ei}(T_e, T_i) \qquad (6)$$

with $W^{i\to i-1} = \sum_{k=0}^{i-1} \dot{n}_k$. The Debye approximation for the quasi-particle shifts Δ_a allows for the derivation of explicit equations for the species temperatures. This enables us to study the interesting interplay of ionization dynamics, temperature relaxation and correlation effects. However, the Debye approximation limits the results to weakly nonideal plasmas. An extension to systems with strongly coupled ions can be found in [10, 19].

Figure 1 shows results for the equilibration of a lithium plasma whose initial values—$T_e(0) > T_i(0)$, $Z(0)$ larger than the equilibrium value—are typically found in laser-produced plasmas. In the first 20 ps, the electron temperature is almost constant since the energy transfer to the ions is approximately compensated by the release of binding energy in the recombining plasma. In the following relaxation stage, the recombination results in an overall heating of the plasma. Due to the lowering of binding energy in a nonideal plasma, the full calculation leads to lower species temperatures compared to the ideal case. Nonideality effects on the population kinetics are small in this example because the effects of a lower binding energy and of the lower electron temperature largely compensate each other.

In figure 2, the equilibration of a shock-produced argon plasma is presented. The selected initial degree of ionization is lower than the equilibrium one. Therefore, the electrons are cooled due to further ionization. After approximately 100 ps, the decrease of electron temperature is almost stopped due to the energy transfer from the ion subsystem. In this example, nonideality effects on the temperature evolution are small, but clearly visible in the ionization degree.

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