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Laser Cooling of Recombining Electron–Ion Plasma

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A method of producing and confining ultracold electron–ion plasma with a strongly nonideal ion subsystem is considered. The method is based on the laser cooling of plasma ions by the radiation resonant with the ion quantum transition. A model is developed for the laser cooling of recombining plasma. Computer simulation based on this model showed that the ion nonideality parameter can be as large as ~100. The data obtained demonstrate that the production of ultracold nonideal plasma is quite possible. © *2002 MAIK "Nauka/Interperiodica".*

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In recent years, considerable interest has been expressed in studying ultracold plasma (UP) [1–13]. Experimental works on producing and studying plasmas at cryogenic temperatures (>4 K) were performed earlier and described in book [14]. Interest in such plasmas was mainly caused by the possibility of investigating various elementary processes with low-energy particles. It should be noted that the degree of ionization of plasma produced in these experiments was low ($<10^{-4}$).

In [2–4] the idea was proposed of producing and confining strongly ionized UP by resonance laser cooling and plasma ion localization. In spite of a low particle concentration ($<10^8$ cm^{-3}), the interparticle interaction in such plasma is relatively strong because of the low particle temperature. It is characterized by the nonideality parameter [15]

$$\Gamma_\alpha = \frac{e^2}{ak_BT_\alpha}, \quad a = \left(\frac{3}{4\pi N}\right)^{1/3},$$

where $\alpha = e$ or i, k_B is the Boltzmann constant, e is elementary charge, a is the mean interparticle distance, N is the particle (electron and ion) concentration, and T_α is the ion ($\alpha = i$) or electron ($\alpha = e$) temperature. For the ion subsystem, Γ_i can be much greater than unity. The respective electronic component may be weakly nonideal ($\Gamma_i \ll 1$), but its temperature is relatively low because of cooling due to the elastic collisions with ions, so that the Debye radius (determined by this temperature) is smaller than the size of cooled area, providing the necessary condition for the existence of electron–ion plasma.

Note that, despite the great progress in utilizing the laser-cooling and atom–ion localization methods [16, 17], recombining electron–ion plasma has not been studied in this context so far. One may anticipate that the extension of these methods to plasmas will assist in preparing new physical objects in laboratory conditions. In particular, a UP with strongly nonideal laser-cooled ionic component is among such objects. This plasma is of considerable interest due to the following reasons.

It is the natural physical implementation of the classical three-dimensional model, so-called one-component plasma (OCP) (ideal electron subsystem acts as a neutralizing background), which is widely used in theoretical studies of phase transitions in Coulomb systems [15]. For this reason, this system is a highly suitable object for the experimental study of the liquid–(Wigner)crystal transition [15] predicted by the OCP theory. The possibility of varying Γ_i in laboratory (by controlling laser parameters) is very important for studying the properties of phase states and transitions between them in quasi-neutral strongly ionized plasmas.

Interest in UP has been grown due to recent experiments [5–7], in which it was produced by near-threshold photoionization [18] of preliminarily cooled Xe atoms. The authors of experiments [5–7] assumed that the electron and ion temperatures were as low as 0.1 and even 10^{-3} K, respectively, for the concentrations of charged particles ~10^8–10^9 cm^{-3}; i.e., plasma should be strongly nonideal for both components. However, the experimental results ran counter to the assumption about very low particle temperature. In a number of subsequent works [8–13], these experiments were analyzed, and it was shown that the relaxation of both subsystems to the minimum-potential-energy state in times $\tau_e \sim \omega_e^{-1}$ and $\tau_i \sim \omega_i^{-1}$ (ω_e and ω_i are the electron and ion plasma frequencies) increases their kinetic energy by $\sim e^2/a$, where a is the mean interparticle spacing. The corresponding nonideality parameters are Γ_e, $\Gamma_i \sim 1$. Further rise in electron temperature is caused by the recombination-induced heating. Therefore, this method allows one to produce UP with the nonideality parame-

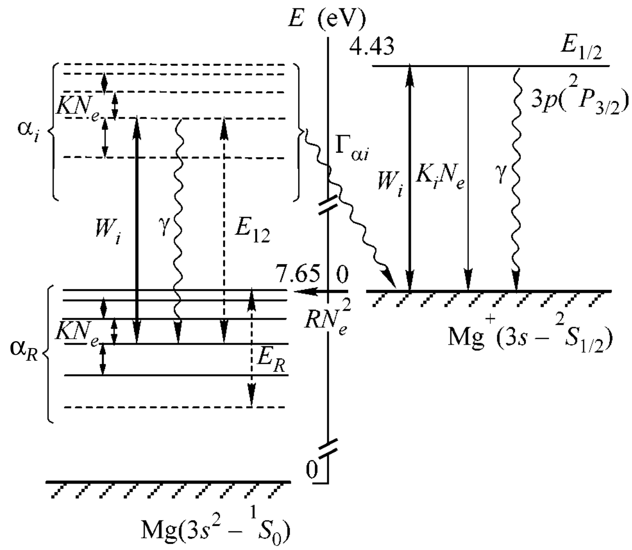

Fig. 1. Scheme of elementary processes: α_i and α_R are the autoionizing and Rydberg atomic states, respectively; E_{12} is the ion excitation energy; E_R is the energy [22] above which the electron-impact-induced de-excitation rate is higher than the spontaneous decay rate. The following processes are also shown: W_i are the laser-induced transitions; KN_e denote the electron–atom inelastic collisions; K_iN_e is the electron-impact-induced ion de-excitation; RN_e^2 is the three-particle recombination; Γ_{ai} is the autoionization decay; and γ is the spontaneous decay of an excited ion.

ter <1 and the lifetime less, at least, than the plasma expansion time.

In our opinion, the combination of two methods—creation of initial UP by near-threshold photoionization followed by laser cooling and ion localization by resonant radiation—is the promising method of producing long-lived UP with strongly nonideal ion subsystem. Such is the case, because the ion heating upon the relaxation to equilibrium distribution is compensated by laser cooling while the plasma expansion is prevented by the ion localization in optical trap and, correspondingly, electron localization by the light-induced ambipolar potential [2, 19].

Note also that the ion-cooling laser radiation affects not only the translational but also the ion internal degrees of freedom. The formation of excited ions initiates a number of elementary processes that complicate the plasma cooling pattern. In particular, the superelastic electron collisions with excited ions and the formation of Rydberg atoms and autoionizing states in the recombining UP are such processes.

In this work, computer simulation was carried out for the plasma laser-cooling dynamics with the aim of determining the range of attainable UP parameters.

Let us consider a "cold" rarefied plasma with a particle temperature of <100 K and a concentration of $<10^9$ cm^{-3}, which can be produced by near-threshold photoionization. Considering the results of works [11–13], we assume that initial temperatures satisfy the condition $\Gamma_e < 1$ and $\Gamma_i \sim 1$. Let the plasma be exposed to the monochromatic radiation [in the form of standing wave with amplitude $E = E_0\cos(k\mathbf{lr})$ along the $\mathbf{l}$ direction] quasi-resonant with the quantum transition of plasma ions and having frequency ω red-shifted from the resonance frequency ω_{21}: $\omega - \omega_{21} = \Delta < 0$. Then the friction force acting on ions in the weak-saturation $|V| \ll \gamma, |\Delta|$ and slow-ion $\gamma \gg k\sqrt{\varepsilon_i/m_i}$ case can be written as [20]

$$\mathbf{F} = m_i\chi(\mathbf{vl})\mathbf{l}, \qquad \chi = \frac{\hbar k^2\gamma\Delta|V|^2}{m_i(\Delta^2+\gamma^2/4)^2}, \qquad (1)$$

where m_i is the ion mass, χ is the friction coefficient, V is the Rabi frequency, γ is the ion excited-state spontaneous-decay rate, and $\mathbf{v}$ is the ion velocity.

The conditions

$$\gamma \gg \omega_i; \quad \tau \ll \tau_0$$

are considered, where $\tau = \max(\nu_{ii}^{-1}, \omega_i^{-1})$, ν_{ii} is the frequency of elastic interion collisions, and $\tau_0 = \chi^{-1}$ is the ion cooling characteristic time.

Due to the elastic collisions with ions, electrons are also cooled, but the electron cooling rate is lower than that of ions if $\tau_0 < (m_e\nu_{ei}/m_i)^{-1}$ (m_e is electron mass and ν_{ei} is the frequency of elastic ion–electron collisions). As a result, the ion subsystem may be strongly nonideal ($\Gamma_i \gg 1$), with the electron state remaining weakly nonideal. Despite the low concentrations, the three-particle recombination rate is high, because the initial particle temperatures are low. Besides, this recombination is distinctive in that the electron is captured to highly excited (Rydberg) atomic levels followed by their electron-impact de-excitation down along the energy axis.

As a result, the cooling irradiation remains resonant with the ion core of the formed Rydberg atom, and the atom undergoes transition to the autoionizing state upon core excitation. This results in the situation corresponding to the method of producing autoionizing states by the "excitation of isolated core" [21].

The subsequent autoionizing atomic decay again results in the formation of an ion and an electron, thereby preventing the recombination. Figure 1 is the schematic of the main elementary processes involved in our model.

As a result of autoionization and superelastic electron collisions with excited ions, hot electrons appear with energy ε_h equal to the resonance ion-transition the energy E_{12} appreciably higher than the kinetic energy ε_e of thermalized electrons. This results in the formation of two groups of electrons, because the energy exchange between them is hampered due to small elastic-scattering cross sections $\sigma_{ee} \sim \varepsilon_h^{-2}$. The formation of hot electrons also brings about recoil-induced ion heating. The recoil energy is $\varepsilon_r \approx m_e E_{12}/m_i$.

Apart from the above-mentioned processes, there are some other processes influencing the ion kinetic energy. Among these are ion heating caused by the quantum fluctuations of radiative forces [20] and decrease in the ion kinetic energy as a result of weakening interparticle Coulomb interaction in the recombination.

Plasma dynamics depends on the size of the region and the way of localization. In our opinion, a purely optical trap based on the use of rectified gradient forces in bichromatic laser fields is most promising for the localization [23], because it is free from the disadvantages inherent in the traditional plasma magnetic confinement methods (magnetohydrodynamic instabilities are possible in nonuniform magnetic fields). The depth U_0 of such a trap can be as large as ~10 K [23]. If the characteristic trap size $L \ll \lambda_h$, where λ_h is the mean free path of hot electrons, the latter will freely escape the trap (in the ambipolar regime with the same number of ions). Although this reduces plasma concentration, the contribution of these electrons to the heating of the remaining thermalized electrons can be ignored. In what follows, the conditions

$$\varepsilon_e < U_0, \quad \varepsilon_h \gg U_0, \quad \varepsilon_r > U_0 \tag{2}$$

are assumed to be fulfilled. This signifies that the thermalized electrons with mean kinetic energy ε_e are confined in the trap, while the hot electrons freely escape it.

With allowance for this, the dynamics of mean kinetic energies ε_e and ε_i of the thermalized electrons and ions and their concentrations N_e and N_i can be described by the set of equations

$$dN_e/dt = -j_0 - K_i N_e N_{2i}; \tag{3}$$

$$N_{2i} \approx \frac{|V|^2}{\Delta^2 + (\gamma/2)^2} N_i, \quad N_i = N_e; \tag{4}$$

$$\frac{d\varepsilon_e}{dt} = Q_r - \frac{2m_e}{m_i}\nu_{ei}(\varepsilon_e - \varepsilon_i); \tag{5}$$

$$Q_r = (\varepsilon_e + E_R) j_0 - \sum_{n_R}^{n_c} (E_R - E_n)\Gamma_n; \tag{6}$$

$$\frac{d\varepsilon_i}{dt} = \frac{2m_e}{m_i}\left(K_i N_{2i} + \sum_{n_R}^{n_c}\Gamma_n\right)\frac{E_{12}}{N_i} + \Lambda + \frac{2m_e}{m_i}\nu_{ei}(\varepsilon_e - \varepsilon_i) - \frac{d(U_i N_i)}{N_i dt} - \chi\varepsilon_i, \tag{7}$$

where j_0 is the classical [24] recombination flux. The second term on the right-hand side of Eq. (3) accounts for the escape of thermalized electrons to the group of hot electrons through the superelastic collisions with excited ions, where K_i is the electron-impact ion-deexcitation rate constant, and N_{2i} is the concentration of excited ions. It is described by Eq. (4), which is obtained in the quasi-stationary approximation valid under the condition

$$\gamma \gg \tau_r^{-1}, \tau_h^{-1}, \tag{8}$$

where τ_r is the characteristic recombination time and τ_h is the characteristic time of electron recombinational heating. Our estimates show that condition (8) is fulfilled for the concentrations $N_e = 10^5$–10^9 cm^{-3} and $\Gamma_e \sim 0.1$. In Eq. (5), the first term on the right-hand side accounts for the electron recombinational heating with the transition of some Rydberg atoms to the decaying autoionizing states; Γ_n is the number of atoms excited in unit time from the state with principal quantum number n to the appropriate autoionizing state (ICE mechanism) followed by the decay of the latter; E_R is the energy above which the electron-impact-induced deexcitation rate is higher than the spontaneous decay rate; E_n is the electron binding energy in the nth state; n_c corresponds to the upper limit of bound states; and $n_R = \sqrt{\mathrm{Ry}/E_R}$. The second term is responsible for the energy exchange in elastic collisions of thermalized electrons and ions (as shown in [25], the pair-collision approximation can be used for weakly nonideal electron subsystem for an arbitrary value of Γ_i) with frequency ν_{ei}. The first term for the ion kinetic energy on the right-hand side in Eq. (7) describes the ion heating by virtue of the recoil energy arisen in the formation of hot electrons; $\Lambda = (\hbar k)^2\gamma^2|V|^2/[2m_i(\Delta^2 + \gamma^2/4)]$ describes the ion heating due to quantum fluctuations of radiative forces [20]; $U_i = -\xi e^2/a$ [26] is the potential energy of interacting ions ($\xi \sim 1$); and the corresponding term in Eq. (7) accounts for a change in this energy in recombination. The value of Γ_n was determined in the weak-field limit from the population balance equations for autoionizing states in the quasistationary approximation, whose validity follows from condition (8). In so doing, the model of fast mixing between the states with different orbital quantum numbers l, the condition $\Gamma_n \ll j_0$, and the features in the dependence of the autoionization rate Γ_{nl} [27] on l were used.[1] In the model considered, $\Gamma_n = \Gamma_n(|V|, \Delta, \gamma, N_e, \Gamma_{nl})$ is a function of field parameters, characteristics of ion quantum transition, concentration of thermalized electrons, and a functional of autoionization rate Γ_{nl} and j_0 is expressed by the classical formula.

Since electrons in the course of ion cooling are heated due to three-particle recombination (Γ_e decreases, as is confirmed by the numerical experi-

[1] With an increase in l at a fixed n, the autoionization rate Γ_{nl} rapidly decreases (by several orders of magnitude) and the contribution to Γ_n comes only from the states with $l \le l_{\max}$ ($l_{\max} \lesssim 10$) [27, 28], so that one may put $\Gamma_{nl} = 0$ at $l > l_{\max} \ll n$).

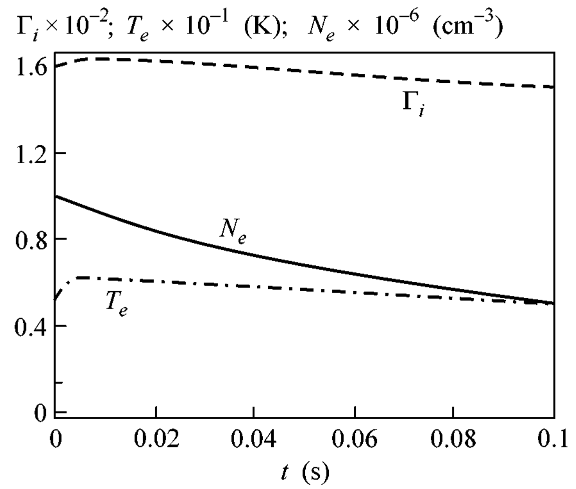

Fig. 2. Dynamics of plasma parameters for $N_0 = 10^6$ cm^{-3}, $\Delta = 2 \times 10^9$ s^{-1}, and electron initial energy $\varepsilon_{e0} = 1$ K.

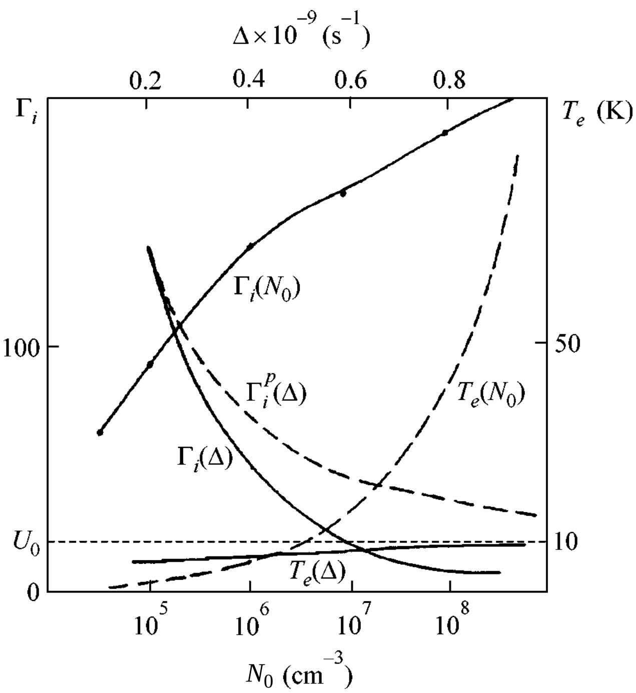

Fig. 3. The nonideality parameter and the electron temperature as functions of N_0 (for $\Delta = 2 \times 10^8$ s^{-1}) and Δ (for $N_0 = 10^6$ cm^{-3}).

ments), they can be considered weakly nonideal and forming ion-neutralizing background.

Computer simulation of model (3)–(7) was carried out for the Mg ions with the initial concentration $N_0 = 10^9$–10^5 cm^{-3}, detuning $\Delta = 2 \times 10^8$–10^9 s^{-1}, and Rabi frequency $|V| = 10^8$ s^{-1}.

Figure 2 demonstrates the dynamics of plasma parameters (Γ_i, ε_e, N_e) in the course of cooling. It turned out that quasistationary values of parameters are established in a relatively short time ($<10^{-4}$ s) and then slowly change because of a decrease in plasma concentration as a result of the escape of hot particles (main reason) and the recombination. Despite the low initial electron temperature, the recombination plays a considerable role only at the initial moment. Because of the fast recombinational electron heating, the rate decreases rapidly and the escape of hot particles from the cooling region plays the main role. Note that a high $\Gamma_i \sim 160$ value is achieved in a rather short time, after which it changes only slightly upon decreasing plasma concentration.

The nonideality parameter is shown in Fig. 3 as a function of concentration $\Gamma_i(N_0)$ and detuning $\Gamma_i(\Delta)$. The Γ_i values correspond to the time $t = 0.1$ s. Similar dependences for the maximal electron temperature are also shown in the figure. One can see that the character of $\Gamma_i(N_0)$ dependence alters at $N_0 \geq 10^6$ cm^{-3}, because the processes change their roles: at small N_0, the "fluctuation" heating mainly limits the ion cooling; as N_0 increases, the electron–ion energy exchange becomes dominant. A change in the roles of processes is also manifested by the deviation of the $\Gamma_i(\Delta)$ dependence from the $\Gamma_i^p(\Delta) \sim 1/|\Delta|$ dependence obtained for $|\Delta| > \gamma$ on the assumption that fluctuation heating dominates.

The dependences shown in Fig. 3 can be used to determine the range of N_0 values that are admissible for the plasma localization in a trap with depth U_0. For example, the concentrations $N_0 \leq 3 \times 10^6$ cm^{-3}, for which the maximal temperature of thermal electrons does not exceed 10 K, are admissible for $U_0 = 10$ K. Nevertheless, $\Gamma_i \sim 150$ can be attained even in such a rarefied plasma.

Our studies have shown that the plasma laser cooling is a rather complicated phenomenon, whose specificity is caused by the low energies of charged particles, action of resonance radiation on both translational and internal degrees of freedom of particles and by the plasma localization in trap. Of special note is the stabilizing role of the trap. In the absence of the trap, the plasma would decay, due to its expansion, in a time on the order of 10^{-3}–10^{-4} s (even at $T \leq 10$ K).

Our computer simulation has demonstrated that plasma laser cooling in an optical trap is an efficient method of producing long-lived ultracold plasma with a strongly nonideal ion subsystem, which can be used in laboratory studies of phase transitions in the coulombic systems. Note also that the specificity of the elementary processes occurring in cooled plasma allows the use of this method for the formation of Rydberg and autoionizing atomic states and the study of the recombination processes in as yet poorly explored low-temperature and low-concentration ranges and the properties of nonideal plasma.

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