Time evolution of ultracold Coulomb plasma

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In supercooled (nonideal) classical Coulomb system recombination due complex many-particle interaction , which is a result of its sharp slowdown . This phenomenon of slowing down the rate of recombination , as well as many other processes have been investigated by molecular dynamics in a series of papers in 1986 - 1996 years (see [1 - 9]) . Discovered a new state of the Coulomb system in which plasma is recombined according to the known law of 9/2 at low temperatures. This state of the classical Coulomb system has been called a metastable supercooled plasma. While not exist in nature physical object consisting of charged-particle, which would satisfy the condition of strong-coupling . Therefore, despite the active discussion found plasma state and remains at the level of the computing artifact.

But in 1999, with selective laser ionization of xenon atoms supercooled state was obtained metastable supercooled Coulomb plasma, for 10 years prior to that observed in the numerical experiment . Then followed a series of papers, both experimentalists and theorists to study the properties of a new physical object , called an ultracold plasma (ultra cold plasma - UCP). Were rediscovered and reconfirmed many of the results obtained in 10-20 years earlier [10 - 18].

In this paper, based on the molecular dynamics calculations , studied the evolution of ultracold plasma at the initial stage , when a cloud formed after photoionization immobile atoms and electrons occupies a fixed volume.

Formation of metastable state passes through a phase of slow recombination fill their bouded ion- electron states. Ultracold neutral system charged particles (plasma cloud in trap), formed by the selective ionization of cold atoms, in the relaxation process passes through two stages. On the first, with little change in the density of the plasma is the formation of a metastable state. In which there is a balance between the free electrons and Rydberg atoms. Investigation of parameters and kinetic characteristics of this plasma is of fundamental problem because of the high degree of plasma coupling. In the second stage of evolution is an expansion of the plasma in the surrounding area, further hypothermia and possibly plasma phase transition to the crystalline phase. Most of the experimental work is devoted to the relaxation of the plasma is in its expansion in surround gas. We consider the relaxation of the plasma in the first phase, which is under experimental conditions correspond to the times of less than 1 microsecond. At this stage, without changing the plasma density due to the expansion. The main physical process is the established of quasi-stationary state of plasma.

We consider the time evolution of the strongly coupled Coulomb system, in which the total energy at the initial time is zero. By the molecular dynamic method is obtained the solution for a system of 2000 particles in the range of 8000 inverse plasma frequencies. It is shown that under conditions typical for experiments with ultracold plasma, the coupling parameter of such plasma can not reach high values nonideality due to the recombination heating.

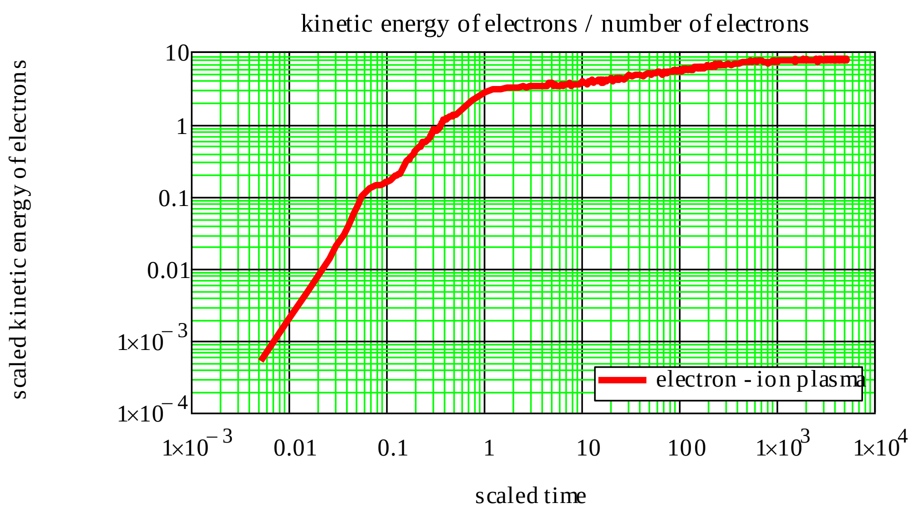
Problem statement and calculation results. A system of an identical number N = 1000 of oppositely charged particles initially immobile and uniformly distributed within a counting cell, i.e., a cube with edge L and specularly reflecting walls, is considered. The cube sizes were chosen from the condition $nL^3 = N$, where n is the numerical ion density which was set to 10^{12} /cm^3 . It was assumed that positively charged particles (ions) have elementary charge *e* and in_nite mass, i.e., they are immobile during the calculation. The electron charge *e* and mass *m* were chosen according to their real values.

The system characteristics were calculated depending on the parameter an $an^{1/3} = 0.01 \div 0.1$ defining the relative potential well depth. The dependence of the characteristics of the system with zero total energy on the potential well depth appears rather strong. However, proper attention is not paid to this factor in many studies, since long-term and high-accuracy calculations are required to reveal this effect.

The described physical system of 2N Coulomb particles is characterized only by the mass, charge, particle density and diameter. As a length unit, we choose the Wigner -Seitz sphere radius for particles of the same type, $r_{WS} = (3/4\pi n)^{1/3}$; as a time unit, we take the inverse plasma frequency $\tau_0 = \omega_{plasma}^{-1}$, where $\omega_{plasma} = (4\pi e^2 n/m)^{1/2}$, and we normalize all energy values to the energy of the interaction of two particles with the elementary charge on the Wigner - Seitz radius e^2/r_{WS}. The chosen physical system is a microcanonical ensemble, its dimensionless average characteristics depend only on the number of particles in the system and the potential well depth in dimensionless units an $an^{1/3}$. Surely, the region shape has a certain effect; however, as calculations show, the difference, e.g., between the cube and sphere at the same number of particles in them, leads to the difference in average characteristics by the value much smaller than 1%. The average characteristics of electrons are determined by time averaging, i.e., the equality of averages over the ensemble and time is assumed (the system ergodicity hypothesis).

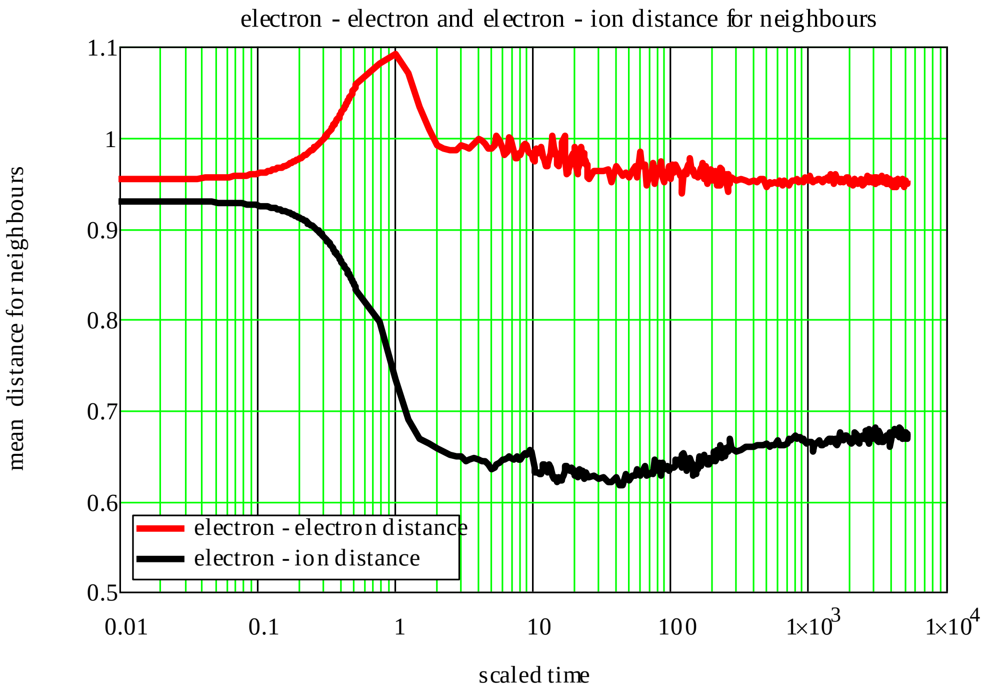
The dependence of the system characteristics on the number of particles is often discussed; however, attention is usually paid to only one aspect, i.e., the sufficiency of the number of particles to achieve desirable statistical validity. In this context, the procedure of multiply repeated calculations with a small number of particles and different initial conditions is sometimes used. However, the effect of the boundary on the system characteristics can be rather considerable in this case.

To study the time evolution of equiprobably distributed within the counting cell and initially immobile electrons by the molecular dynamics method [1, 2], trajectories of N = 1000 electrons (ions were supposed to be infinitely massive and immobile) were calculated and the following characteristics of the electronic subsystem were calculated:



the time dependence of the electron kinetic energy (Fig. 1);

the time dependence of the distances between nearest neighbors (electron -ion and electron - electron) (Fig. 2);



In all _figures, the time $\tau = \omega_{plasma} t$ is measured in inverse Langmuir (plasma) frequencies $\omega_{plasma} = (4\pi e^2 n_e / m_e)^{1/2}$, and the distance between neighbors is normalized, as is conventional in most studies of ultracold plasma, to the Wigner_Seitz sphere radius for particles of the same type, $r_{WS} = (3/4\pi n_e)^{1/3}$.

The calculation results presented in Figs. 1 - 2 show the main stages and features of the evolution of the initially unordered Coulomb system of rest particles. An analysis of the results shows that the Coulomb system evolves from the initially uncorrelated system in several characteristic stages.

In the first stage (we call it the microfield one), particles are uniformly accelerated, and the field for each particle remains unchanged. Accordingly, the ensemble average electron kinetic energy

$$K(t) = \frac{1}{2Nm} \sum_{i=1}^{N} p_i^2(t) \qquad (1)$$

has a quadratic time dependence, since the energy of the xed electron during uniformly accelerated motion is given by

$$K_i(t) = \frac{1}{2} m (eF_i t / m)^2 \propto t^2 \qquad (2)$$

In Fig. 1, the electron energy increases quadratically in time in the range $0 < \omega_{plasma} t < 0.07$; then, in the interval $0.07 < \omega_{plasma} t < 0.15$, the increasing rate is retarded. This retardation is caused by the appearance of the spatial correlation, first of all, the pair electron - electron correlation. Then, in the range $0.15 < \omega_{plasma} t < 1$, the kinetic energy strongly increases mainly due to electron incidence on the charged attracting center. The electrons initially appeared close to each other make their specific contribution. Their contribution to the increase in the kinetic energy at the initial stage is the same as that of the electron -ion interaction; then it slightly decreases, since the repulsion force decreases during separation. For the interaction of the electron with an immobile ion, the situation is reversed: the force increases as the electron is incident on the center; therefore, the energy increases even slightly more rapidly than according to formula (2); then, after transiting the force center, the electron kinetic energy abruptly decreases.

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