Over the barrier electron transfer from a micron sized charged dust particle to an ion in gas discharge plasmas

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Simple semiclassical model for the calculation of the electron transfer cross section from the dust particle to the ion is presented. The key ingredient of the model is the transition rate of the electron from the charged dust particle to the ion as the function of the distance between them. Particularly, over the barrier electron transfer from the micron sized spherical dust particle to the surrounding plasma ion is considered. The cross section of this process for the strong dust particle-ion coupling regime, which corresponds to the case of the room temperature gas discharge plasma is presented. The obtained data were analyzed by comparing them with the ion absorption cross section on the surface of the dust particle. It is found that in the case of micron sized dust particles more than 15 % of ion recombinations with a charged dust particle's electron is due to over the barrier electron transfer. It has been shown that in the considered range of parameters the cross section of over the barrier electron transfer from the negatively charged dust particle to the ion can be presented in a simple analytical form despite strong nonlinearity of the ion-dust scattering problem.

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Complex plasmas (or dusty plasmas) are a special type of plasmas characterized by the presence of micro or nanoparticles, by chemical reactions as well as by the interaction of plasmas with surfaces [1–4]. Research in complex plasmas has given rise to various technological applications, which have appeared only recently [2–4]. At the same time, it is difficult to study complex plasmas both experimentally and theoretically, as they strongly overlap with other fields of physics such us atomic and molecular physics, condensed matter physics, and material science.

It is important to study interactions of plasma particles (electrons, ions, atoms) with the grain surface. The processes on/or near the surface of the grain include recombination and absorption of electrons and ions, thermal emission of electrons, photoemission, secondary emission, electron transfer during interactions between atomic particles or ions and grain surfaces.

The problem of charge transfer between the atomic particle and bulk metal has been studied intensively during the past two decades. The cross section of the electron transfer depends on both the electron structure of the surface and the type of the atom (ion). The electron propagation depends on surface material. For instance, the electron can travel along the surface normal in the case of metals with free electrons [5] or parallel to the surface in case of a metal with a projected band gap [6]. In the case of the dust particle in plasma, calculations of electron transfer and grain charging, in general, are highly complicated tasks and use of the time-dependent Schrodinger equation solvers is not straightforward.. One has to take into account the grain surface heating [7], external electric field, so called wake effect [8–10], dust particle polarization [11, 12], and, what is even more difficult, the modification of the grain surface in plasma [13, 14]. It has been shown that low-temperature plasma treatment (without reactive gases) causes degradation of the surface of melamine-formaldehyde dust particles with developed topography [13]. In the gas discharge containing active gases, the grain surface modifies due to coating by thin nanofilms [14]. For this case, an example of a strongly modified grain surface is presented in Fig.1.

Ion colliding with the dust particle can cause over the barrier electron transfer from the dust particle surface to the ion in the vicinity of the surface. This process should not be confused with the electron-ion recombination on the surface of the grain. The latter process occurs on the characteristic scale of a few Ångstroms, as the microscopic consideration of electrons and ions dynamics near the grain surface using the image potential revealed that electrons captured by the dust particle are trapped at a distance of a few Ångstroms from the surface [16]. Whereas over the barrier electron transfer to the approaching ion can take place at distance ~ 1 μm [17]. In the case of submicron dust particles, J.C. Weisheit and R.J. Upham showed that recombination due to over the barrier electron transfer from the charged dust particle to the ion is the most likely result.

In complex plasmas, as the dust particle charge usually has large values and such classical models as the orbit motion limited (OML) approximation give satisfactory agreement with experimental data, a microscopic consideration of the ion-electron recombination process usually is not the case. On the other hand, actual distance from the dust particle surface at which an ion recombines with charged dust particle's electron is important for correct determination of the momentum flux on the dust particle surface and determination of the dust particles impact on the gas composition. Therefore, evaluation of the importance of the electron transfer from the highly charged dust particle to the ion which at the distance large than several Ångstroms is needed.

In this paper we consider over the barrier electron transfer from the charged dust particle to an ion passing near the grain. Silica and graphite dust particles with size is in the range $0.5\ \mu\text{m} < a < 10\ \mu\text{m}$ are considered. Electron (ion) temperature and density are taken corresponding to the gas discharge plasma parameters as $T_e = 8eV$, $T_i = 0.03eV$, $n_{\text{e(i)}} = 3.75 \times 10^8 \text{cm}^{-3}$.

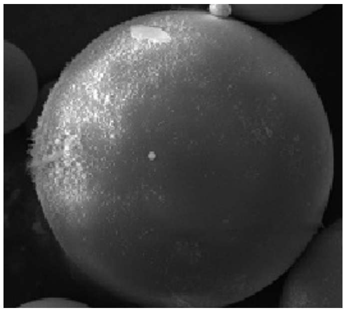

FIG. 1. Modified grain surface in gas discharge plasma

Further, for the determination of the electron release probability, we adopt Bohr and Lindhard type model [24] where we describe capture of the target electron by a charged projectile semiclassically. Such simple models without involving quantum mechanical description proved to be very useful for qualitative and quantitative description of the dust particle charging [18] and charge transfer description [19–23].

Ion -dust particle scattering process is characterized by the coupling parameter $\beta = e^2|Z_d Z_i|/\left(m_i v_\infty^2 \lambda_D\right)$ and by the radius of the dust particle a, here here λ_D is the Debye screening length, $Z_d < 0$ is the dust particle's charge number, $Z_i > 0$ is the ion charge number, m_i is the ion mass, and v_∞ is the initial value (before collision) of the ion velocity.

The electron transfer cross section can be calculated using the following formula [20]:

$$\sigma_r(\beta, a) = 2\pi \int_0^{\rho_{\max}} P(\rho)\rho \mathrm{d}\rho, \qquad (1)$$

where $P(\rho)$ is the passing ion induced electron release probability at a given value of the impact parameter ρ, $\rho_{\max}$ is the maximal values of the impact parameter which defines ions which has the end of trajectories at the surface of the grain.

The electron transfer probability is determined by the time δt spent by the ion in the region $a < r < r_0$ near the grain surface and proportional to the transition rate of the electron from the grain to the ion $\frac{dN_e}{dt} = \nu(\mathbf{r})$, which is a function of the distance between the dust particle and the ion. The electron release probability is found using the following relation:

$$P(\rho) = \int_{r_0+a}^{r_{\min}} \nu(r) \frac{\mathrm{d}\mathbf{r}}{\mathbf{v}(\mathbf{r})}, \qquad (2)$$

where projectile (ion) velocity $\mathbf{v}(\mathbf{r})$ parametrically dependents on the impact parameter ρ and $\mathbf{v}_\infty$, r_0 is the reference distance (at which one starts calculation of the transition probability and dependence on the particular transition mechanism) from the dust particle surface. If Eq. (2) gives a value larger than unity, probability must be taken equal to one.

Classical equation of the ion motion is:

$$\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t} = v_\infty \sqrt{1 - U_{\text{eff}}}, \qquad (3)$$

where U_{eff} is the effective dimensionless potential energy of the ion in the screened field $U_d = \beta \exp(-r/\lambda_D)/(r/\lambda_D)$ of the dust particle taking into account centrifugal force:

$$U_{\text{eff}}(r) = \frac{\rho^2}{r^2} + \frac{eZ_i U_d(r)}{E_\infty}, \qquad (4)$$

here $E_\infty = m_i v_\infty^2/2$ is the initial kinetic energy of the projectile.

Eq. (3) is solved numerically with the initial condition $v|_{\text{t=0}} = v_\infty$ at $r \gg a$ & $r \gg \lambda_D$, and $\rho_{\max}$ is identified by the condition $r_{\min} = a$, where r_0 is the minimal value of the distance between dust particle center and ion.

At the grain surface, the total binding energy of an electron can be estimated as $W = \phi + (\epsilon_F - \epsilon) + zk_B T_e$, where $z = |Z_d|e^2/ak_b T_e$ is the dimensionless dust surface potential, ϵ_F is the Fermi energy of the grain, ϵ is the kinetic energy of the electron, and ϕ is corresponding work function of the dust particle material. The ions which approach on the distance smaller than r_0 to the grain surface can make an electron to leave the surface, where $r_0 = Z_i e^2/W$ is the distance between ion and dust particle surface at which binding energy of a grain electron vanishes and over the barrier electron transfer from the grain to the ion can occur.

Over the barrier non-resonant electron transfer from the grain to the ion was considered in Ref. [17] in the context of interstellar dust. Following J.C. Weisheit, and R.J. Upham [17], the instantaneous rate of the electron release from the dust surface to the ion located at given distance reads

$$\nu(r) \approx 4 \times 10^{15} \eta (a/r)^2 Z_i^2 \ [s^{-1}], \qquad (5)$$

where $\eta \approx 10^{-2}$ is the coefficient determining the proportion of the dust particle's electrons ready for a transition to the ion. It is worth noting that the electron tunneling contribution to the transfer cross section is negligible in comparison with over the barrier electron transfer [17].

The OML approximation is applicable for description of an ion and electron absorption by the dust particle when ions and electrons are collisionless, which means that their mean free paths are much longer than the screening length.

For further analysis, we compare the electron transfer cross section with the ion capture cross section $\sigma_c = \pi \left[\rho_c^{\text{OML}}\right]^2$. Assuming there is no potential barrier for the

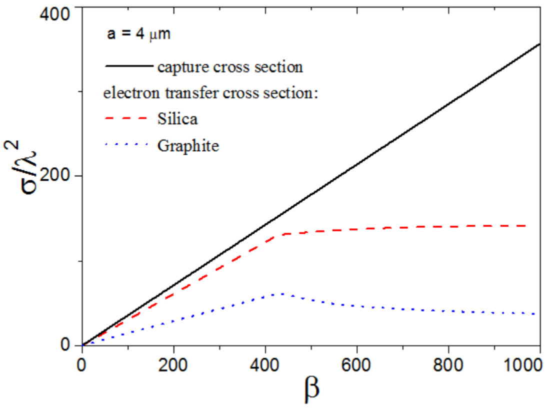

FIG. 2. Over the barrier electron electron transfer cross section is presented for micron sized dust particle in comparison with the full ion capture cross section

ions moving towards the grain, the conservation of angular momentum and energy gives for the collection impact parameter:

$$\rho_{\max} = \rho_c^{\mathrm{OML}} = a\sqrt{1 + \frac{2\beta}{a/\lambda_D}\exp\left(-\frac{a}{\lambda_D}\right)}. \qquad (6)$$

Therefore, the ion capture cross section for our purpose has the following form

$$\sigma_c = \pi a^2 \left(1 + \frac{2\beta}{a/\lambda_D}\exp\left(-\frac{a}{\lambda_D}\right)\right). \qquad (7)$$

In Fig. 2, over the barrier electron transfer cross section is presented for micron sized dust particle in comparison with the full ion capture cross section. In Fig. 3, the ratio of the electron transfer cross section to the ion capture cross section (8) is presented in the cases of the Silica and Graphite dust particles. The interesting feature is that this ratio remains nearly constant up to $\beta \sim 100$. Note that due to strong ion-dust particle coupling considering problem is non-linear. In Figs. 4 and 5, we extend our analysis to the case of different values of the dust particle radius, $0.5\ \mu\mathrm{m} < a < 10\ \mu\mathrm{m}$.

In Fig. 6, the values of the ratio of the electron transfer cross section and the capture cross section are presented as the function of the dust particle radius at $\beta = 10$.

From the provided analysis is it seen that in the range $0.5\ \mu\mathrm{m} < a < 10\ \mu\mathrm{m}$, the electron transfer cross section can be represented by the following analytical formula:

$$\sigma_r = \zeta[a]\sigma_c(\beta, a/\lambda_D), \qquad (8)$$

where $\zeta[a]$ is the ratio of the electron transfer cross section and the capture cross section at any fixed β in the range $1 < \beta \ll 100$. From results of calculations it follows that Eq.(8) is valid for $1 < \beta < 100$. This is a quite important result as it means that previous theoretical models based on the use of the OML absorption cross

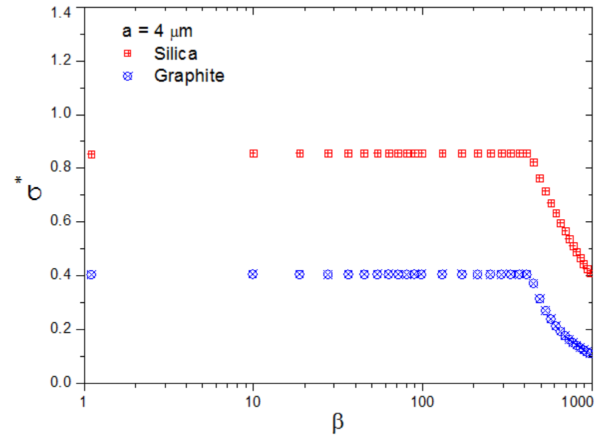

FIG. 3. The ratio of the electron transfer cross section to the ion capture cross section (8) at $a = 4\ \mu$m.

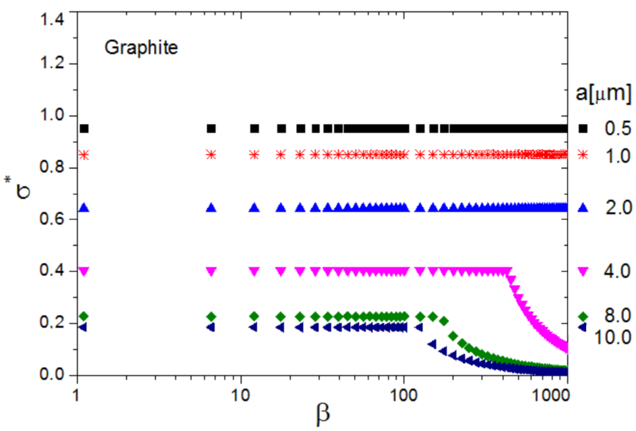

FIG. 4. The ratio of the electron transfer cross section to the ion capture cross section in the case of graphite dust particle (8).

section can be easily modified (or adopted) to consider electron-ion transition effect.

Obtained data on the electron transfer from the dust particle to the ion at the parameters of the gas discharge plasma can be important for the consideration of the momentum exchange between ion and dust particle. Usually it is assumed that ion, which absorbed (collected) by dust particle, give up all it momentum to the dust particle. However, from the provided analysis, it is clear that in the case of the Graphite and Silica dust particles large amount of ions (from 15 % up to 90 %) can be neutralized at distance comparable with the dust particle size. Therefore, first of all, these ions will not give up all its momentum during collision with the surface of the dust particle. Secondly, over the barrier electron transfer effect will increase number of atom close to the dust particle surface and can affect on the dust particle charging. In the case, when the number density of dust particles is large, information about this kind of ion recombination mechanism can be important for the simulation of the

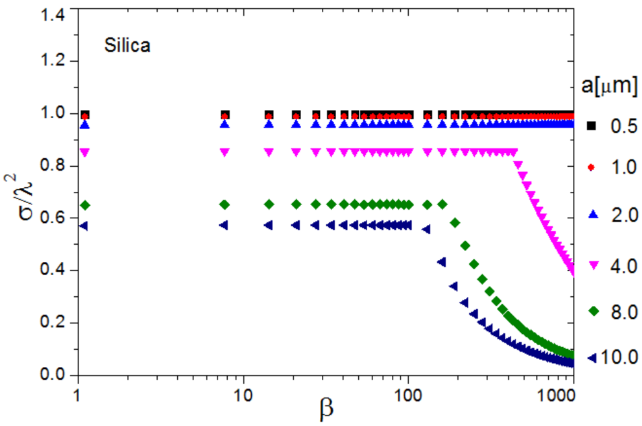

FIG. 5. The ratio of the electron transfer cross section to the ion capture cross section in the case of silica dust particle (8).

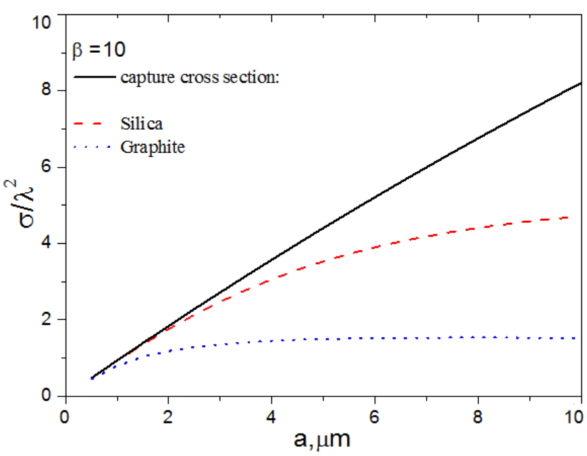

FIG. 6. The values of the ratio of the electron transfer cross section and the capture cross section are presented as a function of the dust particle radius at $\beta = 10$.

gas discharge plasma [25].

In this paper the polarization of the dust particle due to the approach of the ion (image force) is not considered as this effect can be neglected at $\beta > 1$ [11].

In general charge transfer effects between atoms (ions) and the dust particle surface in plasma are purely investigated. This field can be rich in new phenomena as the dust particle can be in a solid as well as melted state, different in size (from $\sim$ 0.01μm up to several micrometers), and due to many excitation mechanism such as surface heating, radiation, plasma waves etc. Results presented in this works indicate that further investigation of the charge transfer during ion-dust particle collision in gas discharge plasmas can be highly important. The key ingredient of the proposed model is the transition rate $\nu(r)$. Further study of the electron transfer during ion-dust particle collision process using more accurate model for $\nu(r)$ is under way and will be presented elsewhere in future. Additionally, we hope that this article will motivate more active work in this direction.

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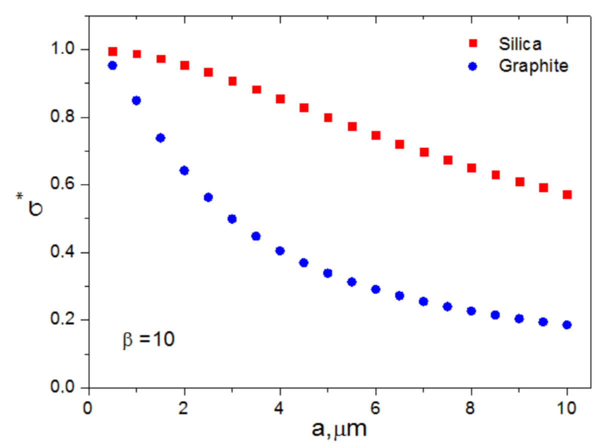

FIG. 7. The ratio of the electron transfer cross section to the ion capture cross section (8) as a function of the dust particle radius at $\beta = 10$.

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