Effect of dust particle polarization on scattering processes in complex plasmas

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Citation: Physics of Plasmas **22**, 063703 (2015); doi: 10.1063/1.4922908
View online: http://dx.doi.org/10.1063/1.4922908
View Table of Contents: http://scitation.aip.org/content/aip/journal/pop/22/6?ver=pdfcov
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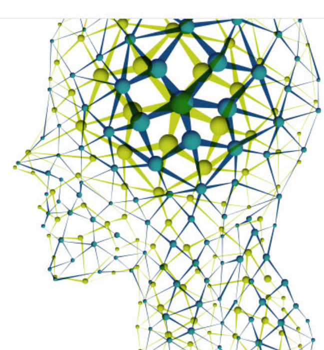

PHYSICS OF PLASMAS 22, 063703 (2015)

Effect of dust particle polarization on scattering processes in complex plasmas

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(Received 15 April 2015; accepted 4 June 2015; published online 22 June 2015)

Screened interaction potentials in dusty plasmas taking into account the polarization of dust particles have been obtained. On the basis of screened potentials scattering processes for ion-dust particle and dust particle-dust particle pairs have been studied. In particular, the scattering cross section is considered. The scattering processes for which the dust grain polarization is unimportant have been found. The effect of *zero angle* dust particle-dust particle scattering is predicted. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4922908]

I. INTRODUCTION

Dusty plasma has been the subject of an intensive research over the last twenty years. There is a large amount of experimental data on static and dynamic properties of dusty plasmas, which were successfully explained in the framework of theoretical models and computer simulation (see, for example, Ref. 1 and references therein), where the interactions between particles were taken as the Yukawa potential.

It is known that the potential formed around the dust particle can deviate from the Yukawa potential.[2–5] In Refs. 6 and 7, it was shown that the potential of a dust particle can have an asymptotic behavior $\sim r^{-n}$, with $n = 2, 3$, due to the loss of ions and electrons on the surface of the dust particle. In Ref. 8, it was shown that such a behavior of the potential has a minor effect on scattering processes in dusty plasmas. There is also a possibility of attraction between likely charged dust particles. One of the possible mechanisms that may cause this process is induced polarization of dust particle[9,10] or polarization of the dust particle + captured ions cloud in an electric field.[11–13] The attraction of one dust particle to the other dust particle in a dc gas discharge as the result of ion focusing got its theoretical explanation in Refs. 14 and 15. A detailed study of ion scattering by dust grains using the Yukawa potential was performed in Refs. 8 and 16.

Using the Boltzmann equation, the authors[17–19] showed that the impact of dust particles on the surrounding plasma can be significant. In particular, it can be explained by the absorption of electrons and ions by the dust grain. The influence of dust particles on the plasma depends on the number density of dust grains and on the dust scattering (absorption) cross section. Therefore, from the point of view of practical application, it is important to study the dust particle-plasma interaction in plasmas where the dust particles appear (complex plasmas), for instance, in different kinds of discharges and in the Tokamak, where dust grains are formed near the wall.[20–23] However, no detailed investigations of the influence of the dust particle polarization on the scattering processes have been carried out (hereafter, dust particle polarization means induction of a dipole moment due to the charge deposition on the grain surface by the electric field of the other particle or by an external electric field). The aim of the present work is to fill this gap. To this end, scattering of ions on a spherical dust grain taking into account dust particle polarization was studied. The dust particle-dust particle scattering process was also studied in the assumption that dust particles can have an induced dipole moment.[24] The absorption of ions and electrons by dust particles and coagulation of dust grains were not considered.

In Sec. II, the ion-dust particle and dust particle-dust particle interaction potentials taking into account dust polarization but neglecting screening by the surrounding plasma are obtained and effective screened potentials are derived. In Sec. III, scattering processes in the complex plasma are considered.

II. SCREENED INTERACTION POTENTIALS

A. Screened ion-dust particle interaction

The interaction potential of the ion with a spherical dust grain without taking into account screening has the following form:[9,25]

$$\phi(r) = -\frac{e^2 Z}{r} - \frac{\xi}{2}\frac{e^2 a^3}{r^2(r^2 - a^2)}, \tag{1}$$

where a is a dust radius, ξ is equal to one for the metal grain and $\xi = (\varepsilon_d - 1)/(\varepsilon_d + 1)$ for the dielectric grain. In Ref. 25, the dust particle charge was calculated by solving Schrodinger equation for the electron with potential (1), and the obtained result was in good agreement with the experimental data. Fig. 1(a) shows the potential (1) for different values of the dust particle charge. The polarization effect becomes important as the dust particle charge decreases.

The adequate investigation of scattering processes in plasma requires taking charge screening into account.[8] In order to obtain the effective screened potential, a well-known formula for the effective potential in the Fourier space is used

$$\tilde{\Phi}(k) = \frac{\tilde{\phi}(k)}{\varepsilon(k)}, \tag{2}$$

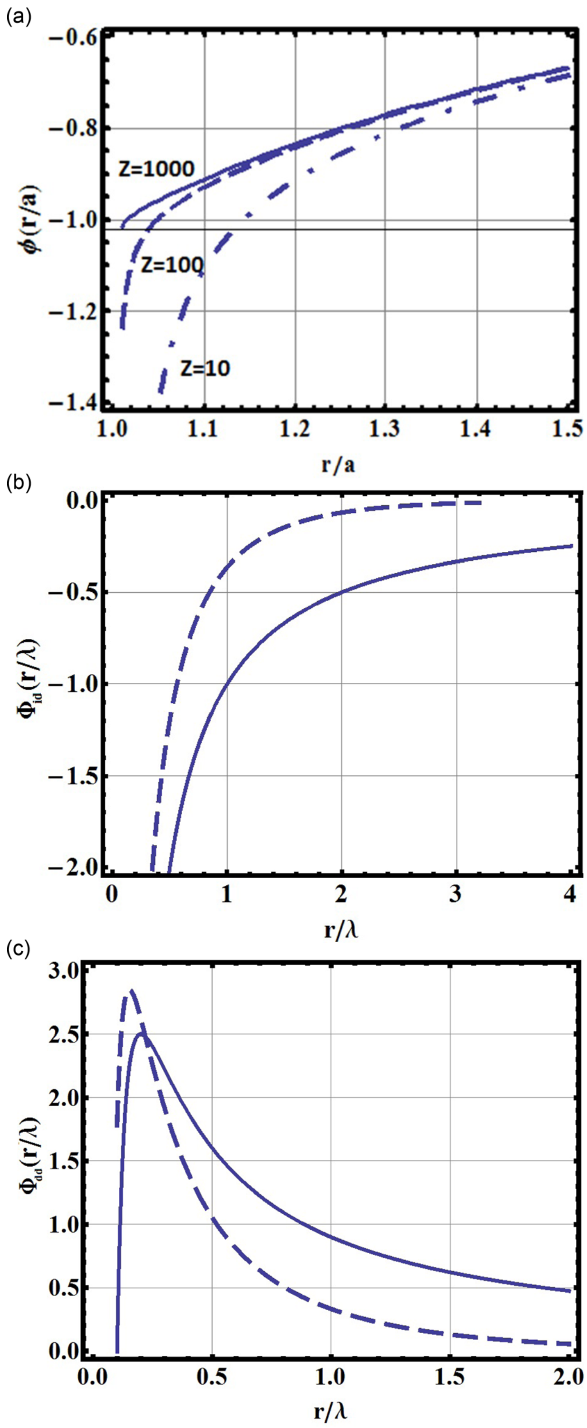

FIG. 1. The interaction potentials between particles of complex plasmas: (a) the potential (1) for the different values of the dust particle charge in units of e^2Z/a; (b) the curves of the screened potential (5) (dashed line) and the potential (1) (solid line) for $Z=10$, $\xi=1$, and $a/\lambda=0.1$ in units of e^2Z/λ; (c) the curves of the screened potential (13) (dashed line) and the potential (11) (solid line) for $\Delta d/(eZ\lambda)=0.1$ in units of e^2Z^2/λ.

where $\tilde{\phi}(k)$ is a Fourier transform of the potential (1) and $\varepsilon(k)$ is the static dielectric function of plasma in linear response approximation[26]

$$\varepsilon(k) = 1 + \frac{k_D^2}{k^2}, \tag{3}$$

where k_D is a screening length (equal to the inverse value of the Debye length λ).

The Fourier transform of the potential (1) is equal to

$$\tilde{\phi}(k) = -\frac{4\pi e^2 Z}{k^2} + \frac{\xi e^2 a\pi^2}{k}(1-\cos(ka)). \tag{4}$$

Substituting Eqs. (4) and (3) into Eq. (2) and performing an inverse Fourier transformation, we can obtain the following screened interaction potential of the dust particle with an ion:

$$\Phi_{id}(r) = -\frac{e^2 Z}{r}\exp(-rk_D) + \frac{\xi e^2 a}{2} \times \left[\frac{1}{r^2} - \frac{a}{r(r^2-a^2)} + \frac{\frac{f(r+a)+f(r-a)}{2} - f(r)}{2rk_D^{-1}}\right], \tag{5}$$

where

$$f(x) = \exp(-xk_D)Ei(xk_D) - \exp(xk_D)Ei(-xk_D), \tag{6}$$

$$Ei(-ax) = -\int_x^\infty dx\, \exp(-ax)/x,$$
$$Ei(ax) = \int_x^\infty dx\, \exp(ax)/x. \tag{7}$$

Fig. 1(b) shows that the potential (5) is screened at large distances. The comparison of potentials shows, that when the condition $a/(2Z\lambda) < 0.1$ is satisfied, the potential (5) can be approximately described by the following empirical formula:

$$\Phi_{id}(r) \simeq -\left[\frac{e^2 Z}{r} + \frac{\xi e^2 a^3}{2r^2(r^2-a^2)}\right]\exp(-rk_D). \tag{8}$$

B. Screened dust particle-dust particle interaction

Let us consider a system of two dust particles. The first dust particle is located in the field of the second one. The distance between dust particles is larger than their sizes. Then, the total potential energy of the system can be expanded in series (see Ref. 27)

$$U = U_0 + U_1 + \cdots. \tag{9}$$

Here, $U_0 = \phi_0 \sum eZ = \frac{e^2Z^2}{r} - \frac{\mathbf{d}_1\mathbf{n}}{r^2}eZ$,

$$U_1(r) = \mathbf{d}_2\mathbf{E}_0 = \frac{\mathbf{d}_2\mathbf{n}}{r^2}eZ + \frac{\mathbf{d}_1\mathbf{d}_2 - 3(\mathbf{d}_1\mathbf{n})\mathbf{d}_2\mathbf{n}}{r^3}, \tag{10}$$

$\mathbf{d}_1$, $\mathbf{d}_2$ are the dusty particles dipole moments. Further, we neglect pure dipole-dipole interaction proportional to $\sim 1/r^3$ assuming that $\mathbf{d}_1\mathbf{d}_2/(eZ\lambda)^2 \ll 1$. This assumption is justified, as, usually, in real experiments on dusty plasmas the Debye radius is larger than the dust particle size $\lambda > a_d$. Therefore, the interaction potential of dusty particles has the following form:[12,27]

$$\phi_{dd}(r) = \frac{e^2Z^2}{r} + \frac{eZ\Delta d}{r^2}, \tag{11}$$

where $\Delta d = (\mathbf{d}_1 - \mathbf{d}_2)\mathbf{n}$, and $\mathbf{n}$ is a unit vector connecting the centers of dipoles $\mathbf{d}_1$ and $\mathbf{d}_2$. The Fourier transform of the potential (11) has the form

$$\tilde{\phi}_{dd}(k) = \frac{4\pi e^2 Z^2}{k^2} + \frac{2\pi^2 eZ\Delta d}{k}. \quad (12)$$

Substituting Eqs. (3) and (11) into Eq. (2), after the inverse Fourier transformation we obtain

$$\Phi_{dd}(r) = \frac{e^2 Z^2}{r}\exp(-rk_D) + \frac{eZ\Delta d}{r}\left[\frac{1}{r} - \frac{k_D}{2}f(r)\right], \quad (13)$$

where $f(x)$ is given in Eq. (6).

The dust grains experience attraction at short distances if $\Delta d < 0$. In Ref. 28, it was shown that such an attraction caused by the charge-dipole interaction can lead to coagulation of dust particles. Further, calculations for scattering processes are made for $\Delta d < 0$.

From Fig. 1(c), it can be seen that the potential (13) is screened at large distances.

In Ref. 29, the following formula for the interaction potential between charged dust particles having dipole moments was suggested

$$\Phi_{dd}(r) \simeq \left[\frac{e^2 Z^2}{r} + \frac{eZ\Delta d}{r^2}\right]\exp(-rk_D). \quad (14)$$

From the comparison of the curves for potentials (13) and (14), it was found that the potential (14) can be used correctly when the condition $|\Delta d|/(eZ\lambda) < 0.1$ is satisfied (see Fig. 2).

In general, during the scattering process the dipole moment of particles is not constant. The dust particle polarization depends on a number of parameters such as particle shape and size, and material and surrounding plasma. It means that in any experiment depending on the above-mentioned parameters, the value of dipole moment varies, and it is difficult to calculate it. Further, we assume that $d = constant$, though the question how good such an assumption remains open, because, as far as we know, there were no experiments where the scattering of two dust particles on each other was studied in order to estimate the impact of the dust particle polarization on the scattering process.

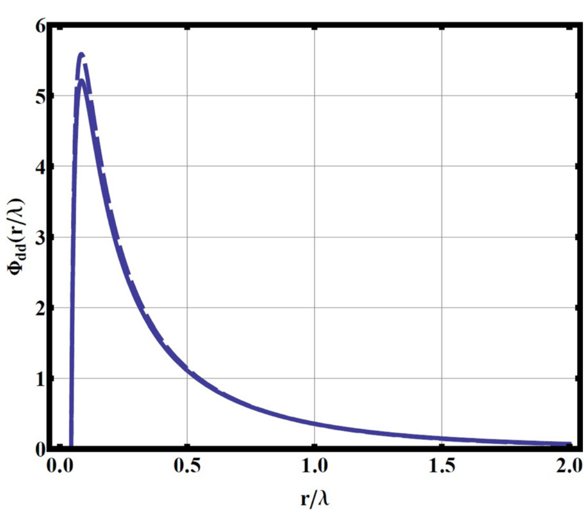

FIG. 2. The curves of the screened potential (13) (dashed line) and the potential (14) (solid line) for $\Delta d/(eZ\lambda) = 0.05$ in units of e^2Z^2/λ.

III. SCATTERING PROCESSES IN COMPLEX PLASMAS

The classical scattering angle for two particles with masses m_1, m_2 and with the interaction potential $U(r)$ for a given impact parameter ρ is equal to

$$\chi(\rho) = |\pi - 2\varphi(\rho)|, \quad (15)$$

where

$$\varphi(\rho) = \rho\int_{r_{min}}^{\infty} \frac{dr}{r^2\sqrt{1 - U_{eff}(r,\rho)}} \quad (16)$$

and U_{eff} is an effective interaction energy in units of the kinetic energy of a projectile $E = mv^2/2$ has the following form:

$$U_{eff}(r,\rho) = \frac{\rho^2}{r^2} + \frac{2U(r)}{mv^2}. \quad (17)$$

The effective potential (17) takes into account centrifugal force. In Eq. (16), r_{min} corresponds to the distance of a minimal approach at the given ρ and is obtained from the equation $U_{eff}(r_{min}, \rho) = 1$. Using $\chi(\rho)$, the scattering cross section can be obtained from the well known formula

$$\sigma = 2\pi\int_0^{\infty}(1 - \cos\chi(\rho))\rho d\rho. \quad (18)$$

A. Ion-dust particle scattering

As the potential $U(r)$, the screened interaction potential of the ion with the spherical dust grain (5) is taken. Further, a metal dust particle is considered $\xi = 1$. The scattering process is characterized by the coupling parameter $\beta = e^2Z/mv^2\lambda$, where m is the ion mass, and by the dimensionless radius of the dust particle $\alpha = a/\lambda$.

Fig. 3 shows the scattering angle for different values of the dust particle charge and dust particle radius. It is seen that the influence of dust particle polarization on ion scattering is stronger for dust particles with smaller charge, but is still negligible up to $Z = 10$. Calculations were made taking into account a physical condition $r_{min} > a$. Fig. 3(b) shows the scattering cross section calculated using the Yukawa potential and the potential (5).

From Fig. 3, it is clearly seen that the polarization of the spherical dust grain leads to an increase in the scattering cross section at $\beta < 1$. For strong ion-grain interaction ($\beta > 1$, which is typical for gas discharge dusty plasmas), the momentum transfer occurs at distances far beyond the Debye length. Hence, the changes in the potential in close vicinity of the grain will not affect the scattering process considerably.

Fig. 4 shows ions trajectories at $\alpha = 1$, $\beta = 30$, and $Z = 10$ calculated using the Yukawa potential and the potential (5). Parameters $\rho/\lambda = 5$, $\rho/\lambda = 4.24$ taken as in Ref. 16 and trajectories obtained in this study are in good agreement with the result of Khrapak *et al.* (see Fig. 1 (Ref. 16)), which

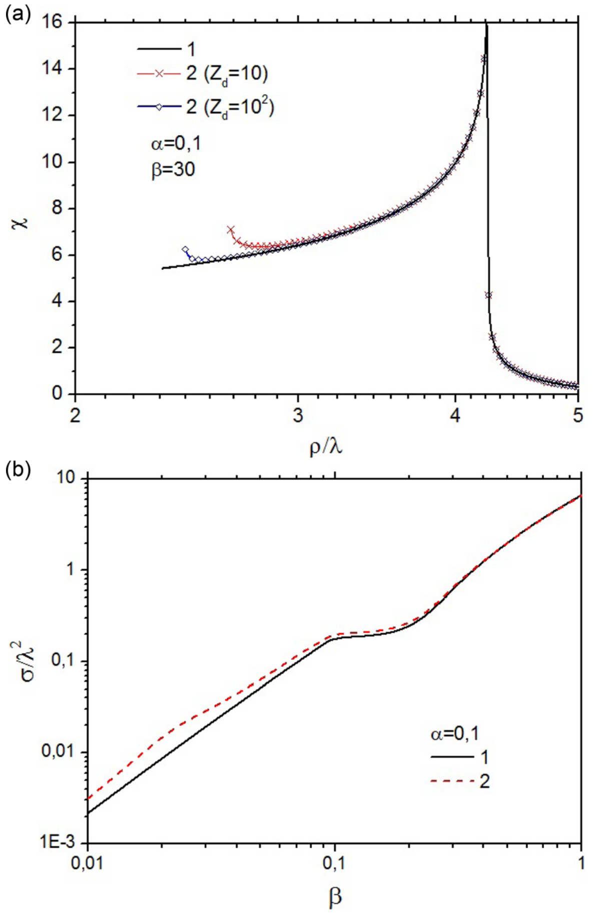

FIG. 3. In (a), the scattering angle obtained using the Yukawa potential (line 1) and the interaction potential (5) of the ion with the spherical dust grain (line 2). In Figure 3(b), the scattering cross section obtained using the Yukawa potential (line 1) and the interaction potential (5) of the ion with the spherical dust grain (line 2) is shown.

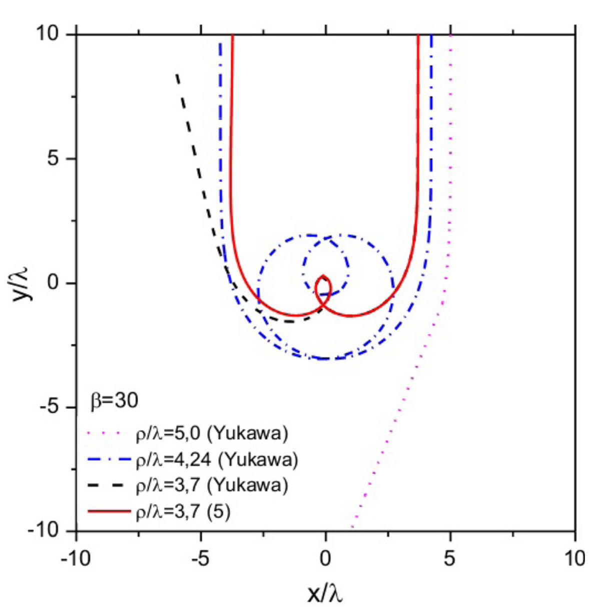

FIG. 4. Ions trajectories during collisions at $\alpha = 1$, $Z = 10$. The scattering center is located at $x = 0$, $y = 0$.

is a good check of our calculations. The figure also shows the trajectories for $\rho/\lambda = 3.7$ obtained using the Yukawa potential and the potential (5).

B. Dust particle-dust particle scattering

As the interaction potential of dusty particles the potential (13), which takes into account an induced dipole moment, is taken. Here, the coupling parameter is equal to $\beta = e^2Z^2/mv^2\lambda$, where m is the mass of the dust grain. Also, the parameter α is redetermined as $\alpha = |\Delta d|/(eZ\lambda)$.

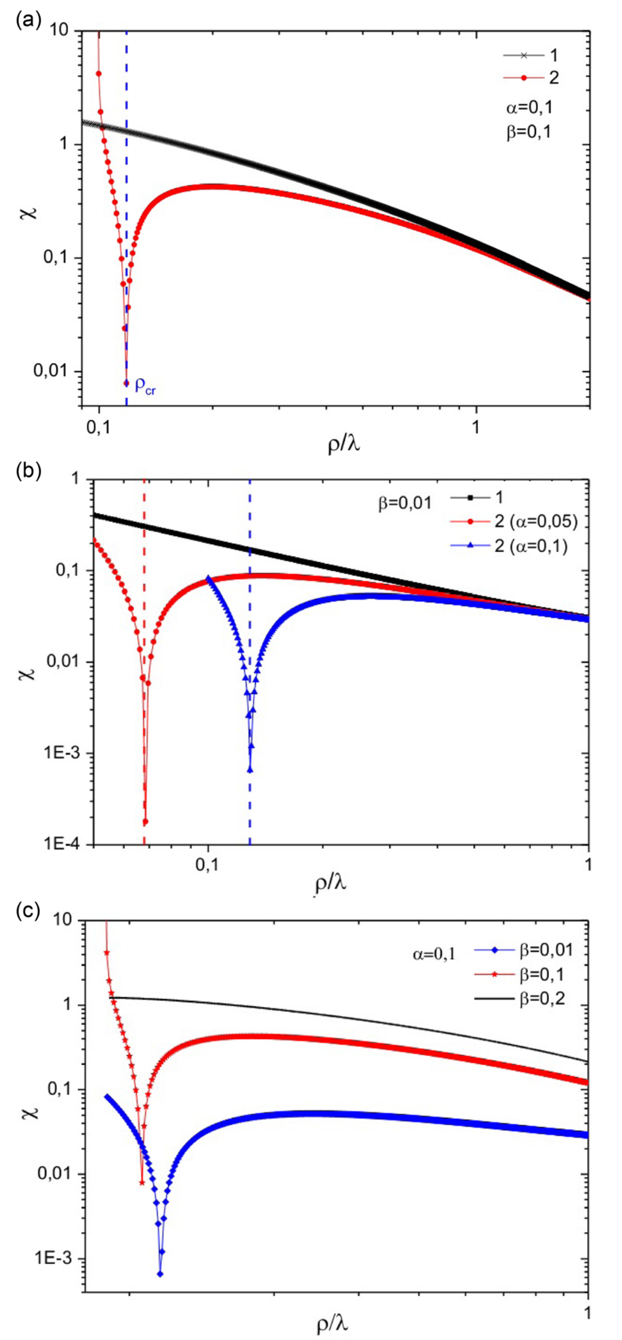

FIG. 5. In (a) and (b), the dust particle-dust particle scattering angle obtained using the Yukawa potential (line 1) and the dust particle-dust particle interaction potential (13) (line 2), which takes into account an induced dipole moment, is shown. In Figure 4(c), the scattering angle obtained using the dust particle-dust particle interaction potential (13) for the different values of β is given.

Figure 5 shows the scattering angle for various α values for $\beta = 0.01$, 0.1, 0.2. It is seen that for $0.005 < \beta < 0.2$ at some *critical* values of the impact parameter ρ_{cr} scattering at a very small deflection angle occurs. This *zero angle* scattering effect is caused by the short range charge-dipole attraction and appears at larger values of the critical impact parameter as the parameter α increases. The corresponding trajectories of dust particles during collisions are shown in Fig. 6. Fig. 7 shows the scattering cross section for $\alpha = 0.05$ and for $\alpha = 0.1$ is shown. It is seen that the difference between the cross section obtained taking into account the induced dipole moment and the cross section obtained using the Yukawa potential appears when the zero angle scattering effect arises. At high energies $\beta < 0.005$, the scattered particle does not experience any deviation from the Yukawa potential; at low energies $\beta > 0.2$, the particle scatters form the Yukawa-type tail of the potential (13) (see bottom figure in Fig. 1) and does not reach the domain where the dipole-charge interaction has a strong effect.

IV. SUMMARY AND CONCLUSIONS

The influence of dust particle polarization on classical scattering processes in complex plasmas was studied using the effective screened potentials. It has been found out that there are scattering processes for which the polarization effect is unimportant. In particular, the polarization of the dust grain has a very small effect on the dust particle-dust particle scattering in the range $\beta < 0.005$, $\beta > 0.2$.

Zero angle scattering is predicted for the coupling parameter β ranging from 0.005 to 0.2. For dust particle charges $Z = 10^3$ and 10^2, the coupling parameter $\beta = 0.1$ corresponds to dust particle energies $E \simeq 172\,\text{eV}$ and $E \simeq 1.72\,\text{eV}$, respectively, where $T_{electron} \gg T_{ion}$ and the ion temperature is taken equal to $T_{ion} = 300\,\text{K}$. In gas discharge experiments, the kinetic energy of the dust particle has the value up to 20 eV.[30,31] Therefore, for low charged dust particles ($Z = 100$), the prediction of the dust particle-dust particle zero angle scattering can be checked experimentally.

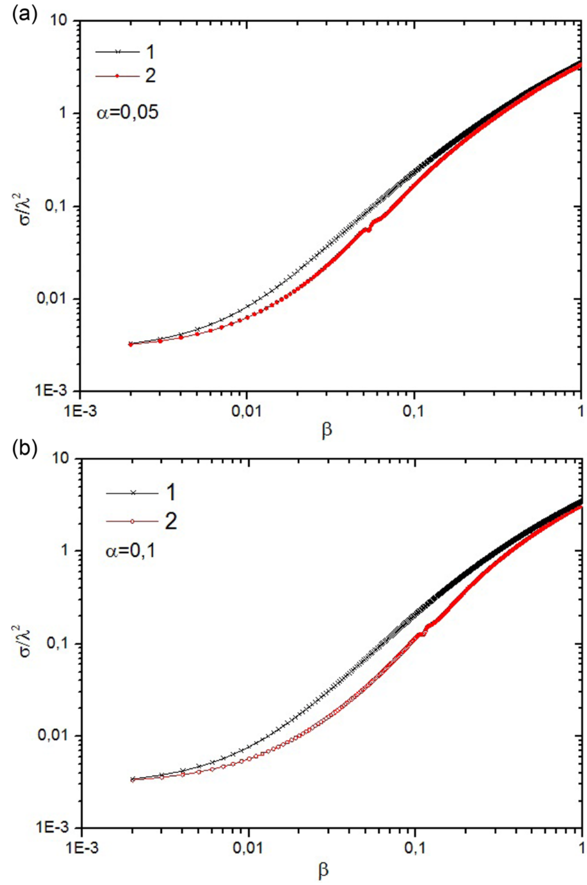

FIG. 7. The scattering cross section obtained using the Yukawa potential (line 1) and the interaction potential (13) (line 2) taking into account an induced dipole moment.

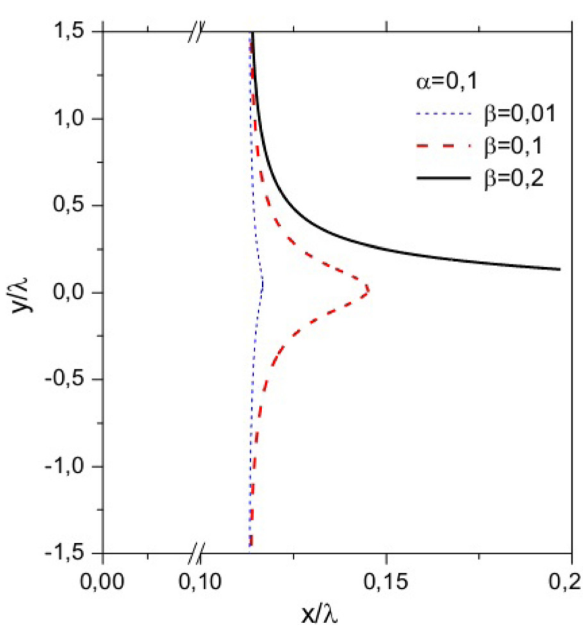

FIG. 6. Dust particles trajectories during collisions for different β at $\alpha = 0.1$. The scattering center is located at $x = 0$, $y = 0$.

It is should be noted that the dust particle can have a dipole moment induced by an external electric field.[29] In this case, the potential (13) can be applied but the scheme from Sec. III can not be used as the spherical symmetry is violated.

ACKNOWLEDGMENTS

This work has been supported by the Ministry of Education and Science of Kazakhstan.

[1]M. Bonitz, C. Henning, and D. Block, "Complex plasmas: A laboratory for strong correlations," Rep. Prog. Phys. **73**(6), 066501 (2010).
[2]G. E. Morfill and A. V. Ivlev, Rev. Mod. Phys. **81**, 1353 (2009).
[3]P. K. Shukla and B. Eliasson, Rev. Mod. Phys. **81**, 25 (2009).
[4]T. S. Ramazanov, S. K. Kodanova, T. T. Daniyarov, and Zh. A. Moldabekov, Contrib. Plasma Phys. **51**, 514–518 (2011).
[5]A. I. Momot, Phys. Scr. **T161**, 014002 (2014).
[6]D. Montgomery, G. Joyce, and R. Sugihara, Plasma Phys. **10**, 681 (1968).
[7]G. Cooper, Phys. Fluids **12**, 2707 (1969).
[8]M. D. Kilgore, J. E. Daugherty, R. K. Porteous, and D. B. Graves, J. Appl. Phys. **73**, 7195 (1993).
[9]V. A. Saranin, Usp. Fiz. Nauk **169**, 453 (1999).
[10]F. B. Baimbetov, A. E. Davletov, Zh. A. Kudyshev, and E. S. Mukhametkarimov, Contrib. Plasma Phys. **51**, 533 (2011).
[11]D. D. Tskhakaya and P. K. Shukla, J. Exp. Theor. Phys. **98**, 53 (2004).

[12]T. S. Ramazanov, Zh. A. Moldabekov, K. N. Dzhumagulova, and M. M. Muratov, Phys. Plasmas **18**, 103705 (2011).
[13]S. K. Zhdanov, A. V. Ivlev, and G. E. Morfill, Phys. Plasmas **16**, 083706 (2009).
[14]P. Ludwig, H. Kählert, and M. Bonitz, Plasma Phys. Controlled Fusion **54**, 045011 (2012).
[15]P. Ludwig, W. J. Miloch, H. Kählert, and M. Bonitz, New J. Phys. **14**, 053016 (2012).
[16]S. A. Khrapak, A. V. Ivlev, and G. E. Morfill, Phys. Rev. Lett. **90**, 225002 (2003).
[17]A. V. Fedoseev, G. I. Sukhinin, T. S. Ramazanov, S. K. Kodanova, and N. Kh. Bastykova, Thermophys. Aeromech. **18**(4), 615 (2011).
[18]S. Iwashita, E. Schüngel, J. Schulze, P. Hartmann, Z. Donko, G. Uchida, K. Koga, M. Shiratani, and U. Czarnetzki, J. Phys. D: Appl. Phys. **46**, 245202 (2013).
[19]G. I. Sukhinin and A. V. Fedoseev, Phys. Rev. E **81**, 016402 (2010).
[20]G. Wattieaux and L. Boufendi, Phys. Plasmas **19**, 033701 (2012).
[21]G. Wattieaux, A. Mezeghrane, and L. Boufendi, Phys. Plasmas **18**, 093701 (2011).
[22]T. S. Ramazanov, A. N. Jumabekov, S. A. Orazbayev, M. K. Dosbolayev, and M. N. Jumagulov, Phys. Plasmas **19**, 023706 (2012).
[23]S. A. Orazbayev, M. M. Muratov, T. S. Ramazanov, M. K. Dosbolayev, M. Silamiya, M. N. Jumagulov, and L. Boufendi, Contrib. Plasma Phys. **53**, 436 (2013).
[24]G. Lapenta, Phys. Scr. **57**, 476 (1998).
[25]F. X. Bronold, H. Fehske, H. Kersten, and H. Deutsch, Contrib. Plasma Phys. **49**, 303 (2009).
[26]T. S. Ramazanov and K. N. Dzhumagulova, Phys. Plasmas **9**, 3758 (2002).
[27]L. D. Landau and E. M. Lifshitz, *Theory of Fields* (Physmathlit, Moscow, 2003).
[28]R. Yousefi, A. B. Davis, J. Carmona-Reyes, L. S. Matthews, and T. W. Hyde, Phys. Rev. E **90**, 033101 (2014).
[29]G. I. Sukhinin and A. V. Fedoseev, IEEE Trans. Plasma Sci. **38**(9), 2345 (2010).
[30]Y. A. Ussenov, T. S. Ramazanov, K. N. Dzhumagulova, and M. K. Dosbolayev, Europhys. Lett. **105**, 15002 (2014).
[31]R. A. Quinn and J. Goree, Phys. Plasmas **7**, 3904 (2000).