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Wake-induced symmetry-breaking of dust particle arrangements in a complex plasma

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A symmetry-breaking disruption occurs in a system of two dust particles with the decrease of the particle separation. This disruption is attributed to the formation of the common ion wake in the system. In the experiment, the particles levitate in the sheath of a radio-frequency (rf) discharge at low gas pressures ($\leq 60\,$mTorr) and their separation is changed by the laser manipulation. The experiment is complemented by molecular dynamics (MD) numerical simulations. The experimental and simulation data agree that the disruption condition corresponds to the common ion wake formation at the interparticle distances less than the electron Debye length.

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The complex plasmas, i.e. plasmas containing solid mesoscopic particles ("dust" particles, larger as compared with the sizes of ions/neutral atoms but lesser than the typical collective plasma scales such as Debye length) appear recently as useful and convenient objects to model numerous fundamental physical phenomena such as phase transitions, diffusion and transport, and symmetry breaking [1, 2]. The ability to study phenomena at the individual particle level allows researchers to directly investigate the kinetics of many fundamental phenomena, attributed previously mainly to the condensed matter physics.

The dust particles in a complex plasma tend to self-organize themselves in various ordered structures such as dust crystals, strings, and clusters [3, 4]. In a typical experiment [3, 4], the dust structures levitate in the sheath region, where the strong ion flow to the electrode is established. The ion flow naturally provides a distinctive direction and reduce the symmetry of the considered system. This is responsible for the vertically aligned crystal structure and string formation.

The nature of particle alignments in systems containing large number of particles can be understood by considering simplified systems of just a few (e.g., two) particles [4 – 9] allowing to elucidate the physics of the reduced symmetry in dust-plasma structures. One of the major factors that affect the symmetry of the dust arrangements in discharge plasma is the ion wake formed downstream the particles in the presence of ion flow, as demonstrated theoretically, experimentally, and numerically [10 – 15]. With this reasoning, the dust particles behave as Cooper-like pairs and the plasma polarization in the ion focus leads to the appearance of the "binding" force that is responsible, e.g., for the formation of dust molecules [4, 11]. Thus the wake changes the symmetry of the particle interaction and therefore the symmetry of the dust structures.

It is well known that the symmetry breaking occurs if a system allows an asymmetric stable state when a controlling parameter (such as order parameter) reaches a certain value [16]. One of the striking observations of the symmetry breaking in a complex plasma was the disruption in the two particle system where the particles changed their arrangement from the horizontal to the vertical one depending on the discharge parameters (pressure or input rf power). It was pointed out that the state of the system is determined by the values of the particle coupling energy and the energy of the horizontal and vertical confinements as well as by the influence of the wake potential [6]. Later, the effect of the horizontal and vertical confinements on the stability of the particle arrangements was analytically considered in Ref. [7]. The further elucidation of the role of the horizontal and vertical confinements was done in the experiment [9] where the symmetry breaking was triggered by applying an additional bias voltage to change the confinements' ratio.

The symmetry breaking in the two particle system generally appeares as an initially continuos change of the position of one particle going closer and below another one followed by an abrupt change of the symmetry (the first particle jumps straight below the second particle) on the second (discontinuous) stage. All previous analyses were concentrated on the first continuos stage. This corresponds to the absense of the bifurcation and allows a simple analytic treatment in terms of the stability of small (linearized) oscillations. The analysis of the second discontinuous stage, as was stressed in Ref. [6], is a rather complicated problem requiring understanding of the ion wake focus characteristics in the presence of the nearby particle and involving the nonlinear wake dynamics that can be adequatly treated by numerical simulations – the issue not resolved at that time.

In this Letter, we report on the experiments of the ion wake-induced symmetry breaking in the two-particle arrangement complemented with molecular dynamics (MD) simulations of the nonlinear ion wake formed in the system of two nearby dust particles. The previous experimental studies [5, 6] where the particle disruptions were triggered by changes in the discharge parameters, i.e., by changes of all parameters in the systems, make proper comparison with the theory and/or simulations deficient. In our experiments, the *disruption was triggered by the laser beam focused on one particle* thus pushing it closer to another particle. In that case the change in the particle separation was accompanied by keeping all other system (plasma) parameters constant, and the discontinuous stage of the symmetry-breaking disruption was induced by changing the interparticle distance only. Note that the laser-assisted manipulation of dust particles was first reported in Ref. [11] where the top particles were shifted by the laser beam, with the bottom particles following the motions of the top ones. This allowed to conclude on the presence of the wake force acting on the bottom particles and to estimate the strength of the wake. Similar experiment was repeated in Ref. [5] where the observed hysteresis in the transitions between the particle arrangemets (due to the changed discharge parameters such as the gas pressure and the input power) was attributed to the influence of the wake. However, the particle disruption triggered by the laser beam has not yet been reported. Ours is a refined experiment allowing us to exclude all other possible controlling factors except for the only controlling parameters, the particle separation, and make a direct comparison with associated numerical simulation. In the simulation, it was observed that the *common* wake focus of the two nearby particles appears when the particle separation is less than the electron Debye length. This interparticle distance exactly corresponds to that for which the particle jump was observed in the experiment. This allows us to relate the discontinuous stage in the change of the particle arrangement with the formation of the common wake.

In the experiments, mono-dispersed melamine formaldehyde dust particles of diameters 2.79 ($\pm 0.06 \mu$m) were used to introduce into an argon rf discharge. The plasma was generated at pressures in the range 20–60 mTorr and a 15 MHz signal was applied to the powered electrode. The peak-to-peak voltage measured on an electrical feedthrough was 25–100 V. The electron temperature, density and plasma potential were measured with a rf-compensated passive Langmuir probe. The electron density is $(2-9) \cdot 10^8\,\mathrm{cm}^{-3}$, the electron temperature is about of 6 eV, and the plasma potential is 15–65 V.

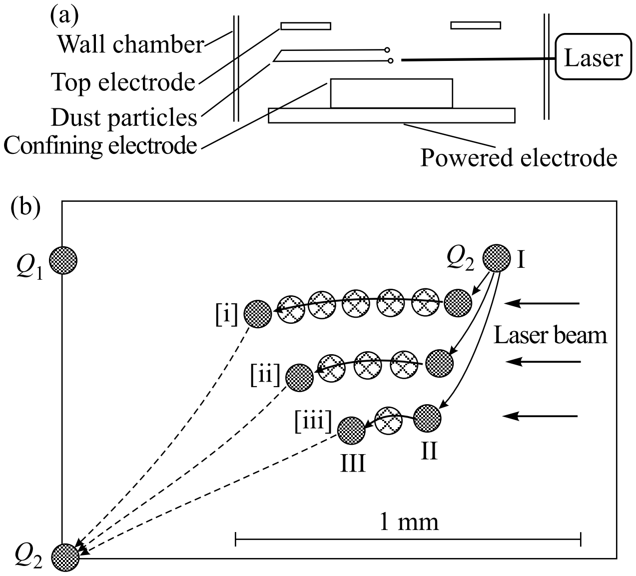

Fig.1. (a) Experimental setup. Two particles levitate in the sheath of the powered electrode of rf discharge argon plasma. The confinement is provided by the rectangular electrode with the size of 20 × 7 mm, and the border height is 4 mm. (b) Sketch of the typical laser-induced disruption of the two-particle ($Q_{1,2}$) arrangement; the transition dynamics for three different cases is shown for the neutral gas pressure of 50 mTorr. Transition I–II is induced by the bias (such as 1.2 V for [i], 2.6 V for [ii], and 3.4 V for [iii]) applied by the confining electrode, transition II–III is induced by the action of the laser. The symmetry breaking disruptions occur at the points III that are different for the particles approaching at the different heights. The jump III–IV (dashed arrows) brings the lower particles to the same position IV below the upper particle

The experimental set up is shown in Fig.1a (its details can be found elsewhere [9]). The main difference of the present setup is that the radial confinement is applied by the rectangular electrode placed on the lower electrode. The dc voltage can be applied to the confining electrode in order to change the horizontal confinement. The dust particles were suspended into the plasma by a shaker allowing to release individual particles. The particles were illuminated using a 20 mW Helium-Neon laser. The second 1 W diode laser was used for the particle manipulation. The diode laser beam was focused on the side particle, and the power of the laser was controlled by the laser diode driver and was varied from 50 mW up to 400 mW. The laser beams enter the discharge chamber through 40 mm diameter windows placed opposite each other. The observation window mounted on a side port in a perpendicular direction allows a view of the light scattered at 90° by the suspended dust particles and provides a vertical cross-section of the dust particles arrangement. Images of the illuminated dust particles were obtained using a CCD camera with a 60 mm micro lens and with a digital camcorder (focal length: 5–50 mm). The video signals were transferred to a computer via a frame-grabber card with 8-bit grey scale and 640 × 480 pixel resolution. The coordinates of the particles were measured in each frame, and individual particles were traced from one frame to the next. After the tracking, the data were placed in a spreadsheet and analyzed. From the data analysis we obtained the particle vertical and horizontal coordinates. The accuracy of the measurement of the particle separation and the levitation height was 30 μm.

In the experiment, the main goal was to induce the symmetry breaking disruption by the change of the particle separation only, in contrast to all preceding experiments. Thus we can single out the effect of the ion wake. The experiment was performed in the following steps. First, we have applied a small confining (in the horizontal) bias (up to 5 V) to force the initial vertical separation (see Fig.1b) because of the strong Coulomb repulsion in the horizontal plane the particles cannot get closer to each other while being at the same height. Then, second, the lower placed particle was pushed in the horizontal direction by the diode laser towards the upper particle. The laser power was increased to shift the bottom particle until it jumps directly under the upper one.

Figure 2 shows the set of the points where the symmetry-breaking disruption occurs for the netural gas pressure of 30 mTorr. We can see from Fig.2 that the disruption occurs when the particle separation is less than the electron Debye length. This takes place for various gas discharge pressures. Table gives the average interparticle distance $D = \sqrt{(\Delta x)^2 + (\Delta z)^2}$ (at which the disruption occurs) in the units of the electron Debye length λ_{De} for different gas pressures. The symmetry breaking takes place when the interparticle distance is between $0.7\lambda_{De}$ and $0.8\lambda_{De}$, being almost unchanged for different gas pressures.

The discontinuous nature of the transition demonstrates that some principal change occurs in the system. Since the discharge parameters and confinements are keeping constant we should assume that with the particle separation decreasing below certain critical value ($\sim 0.75\lambda_{De}$) the particle-particle and particle-plasma interactions are changed dramatically. The most important factor which influence can crucially affect the sudden change in the particle interaction is the ion wake focus behind the particles. Here, we relate the symmetry breaking disruption in the particle arrangement with the qualitative change in the wake, that is to the formation of the *common* wake of two particles when they are sufficiently close to each other.

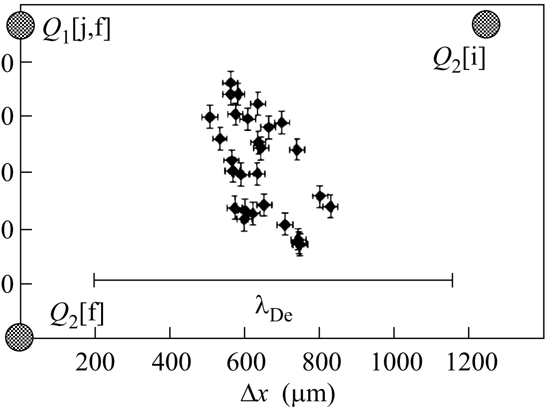

Fig.2. The experimentally determined disruption points for the two-particle $Q_{1,2}$ system (the neutral gas pressure P = 30 mTorr). [i] and [f] stands for the intial and final positions of the particles. The position of the first particle does not change in the transition. The final position of the second particle is always strictly below the first particle. The z-axis represents the vertical separation while the x-axis represents the horizontal separation

The mean interparticle distances for which the symmetry-breaking disruption occurs for different netural gas pressures

Gas pressure P (mTorr)	20	30	40	50	60
Interparticle distance D/λ_{De}	0.77	0.76	0.74	0.72	0.71
Electron Debye length λ_{De} (μm)	1021	944	832	657	588

To prove this hypothesis, we performed a self-consistent three-dimensional (3D) MD simulation of the kinetics of the plasma electrons and ions around two dust grains shifted with respect to each other. To visualize the ion wake focus, we present here the simulated distributions of the ion plasma densities. Details of the numerical technique are described elsewhere [14, 15]. The numerical method involves simulation of the time evolution of the fully ionized ($Z_i = 1$, i.e. the ions are single charged) plasma consisting of N_i positively single-charged ions and N_e negatively charged electrons confined in a simulation box $0 < x < L_x$, $0 < y < L_y$, $0 < z < L_z$, together with the two macroscopic absorbing grains (dust particles), each of diameter $a = 1\ \mu$m, with the infinite masses and the initial (negative) charges $Q_{1,2,0} = Z_{d1,2,0}e = 1000e$, where e is the electron charge.

The ions are introduced in the system at the plane $z = 0$ as a uniform flow in the z-direction with the Mach number $M = V_0/V_s = 1.41$ and the temperature T_i, where $V_s = (T_e/m_i)^{1/2}$ is the speed of the collisionless sound waves, T_e is the temperature of plasma electrons (all temperatures are in energy units, i.e. Boltzmann's constant is unity), and m_i is the ion mass; at $z = L_z$ the ions are removed from the system. The dust particles are placed at $z_1 = L_z/8$, $z_2 = L_z/8 + \Delta z$, and $x_{1,2} = L_x/2 \pm \Delta x/2$, such that $\Delta z, x$ appear as the distances between them in the direction z, parallel to the ion flow, and the direction x, perpendicular to the flow (the other coordinate of the particles is $y = y_0 = L_y/2$). The equations of motion are solved by the Runge–Kutta method of the fourth order with the automatically chosen time step. For the characteristic lengths we have $L_z/3 = L_x/4 = L_y/2 = \lambda_{De}$ where the electron Debye length $\lambda_{De} = 5.256\,\mu$m. The total simulated time of the physical processes is $4.03 \cdot 10^{-8}$ s; this should be compared with the ion plasma period $\tau_{pi} = 2\pi/\omega_{pi} = 0.67 \cdot 10^{-8}$ s.

Figure 3 presents the contour plots of the ion density n_i normalized to $n_{i0} = N_i/L_xL_yL_z$ for $\Delta z = 0.6\lambda_{De}$ and three different distances between the grains. Strong ion focuses are formed behind the dust particles; furthermore, depending on the distance between the particles, the wake maximums are merged at the interparticle distance of $D = \sqrt{(\Delta x)^2 + \Delta z)^2} \sim 0.7\lambda_{De}$ (when $\Delta x = 0.4\lambda_{De}$), the case (b), in contrast to their clear separation at the larger interparticle distance ($\Delta x = 0.8\lambda_{De}$), the case (a). In analogy to the Rayleigh criterion in spectroscopy [17], the beginning of the common wake formation can be determined as the case when the ratio of the ion density between the particles to the mean ion densities behind the particles is the 0.7. The common wake is formed in the case when the ion density between the particles exceeds the ion densities behind the particles.

The simulations for the different ion flow velocities were performed, inluding the case of subsonic ion flow velocities (e.g., $M = 0.8$). The results show that despite some differences in the ion wake formation for the subsonic and supersonic flows, the common ion wake focus formed behind the particles exhibits the same characteristics depending crucially on the particle separation. We also note that the physics of the common wake formation includes complex phenomena of the ion scattering by highly charged macroscopic particles, in particular, the large-angle nonlinear ion scattering that in the simplified case of one dust particle and the absence of the flow was investigated only recently [18, 19].

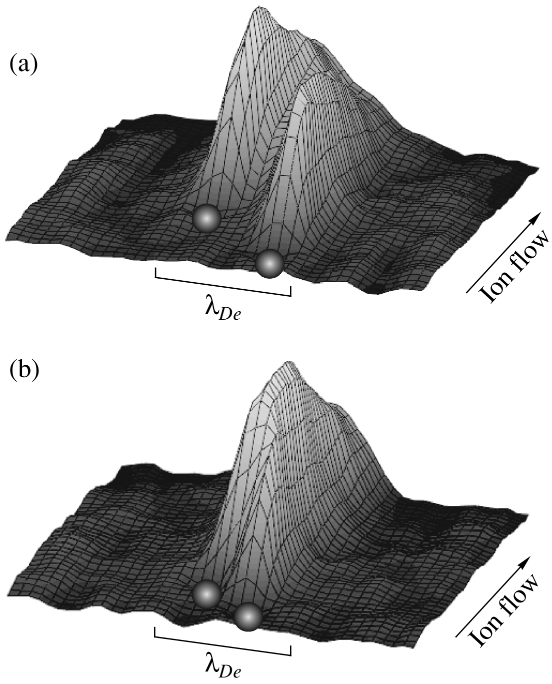

Fig.3. Surface plots of the MD simulated ion wake focus for the two different separations in the direction x perpendicular to the ion flow: (a) corresponds to $\Delta x = 0.8\lambda_{De}$; (b) – $\Delta x = 0.4\lambda_{De}$. Note the formation of the common fully developed wake in the case (b)

The formation of the common ion wake dramatically changes the particle interaction and the symmetry in the system. This, in turn, has to lead to the drastic change in particle position. Figure 4 represents the experimentally observed disruption points along with the results of MD simulation which show the area of the common wake formation. The points of disruption are in very good agreement with the simulation data for the particle separation where the common ion wake is formed. According to Fig.4, the disruption occurs when the common wake is either starting to form (the grey area between the dashed lines) or has already formed (the "common wake" area below the left dashed line). These figure clearly relates the common wake formation and the disruption in the considered system.

The phenomenon of the common ion wake formation gives a new insight on the ordering of dust particles in the sheath region. It is clear that the adequate description of the state of a many-particle system as well as its symmetry and phase transitions has to include, in addition to the standard linearized (or weakly nonlinear such as in the perturbation theory) analysis of the dust oscillation characteristics (stable/unstable modes), the influ-

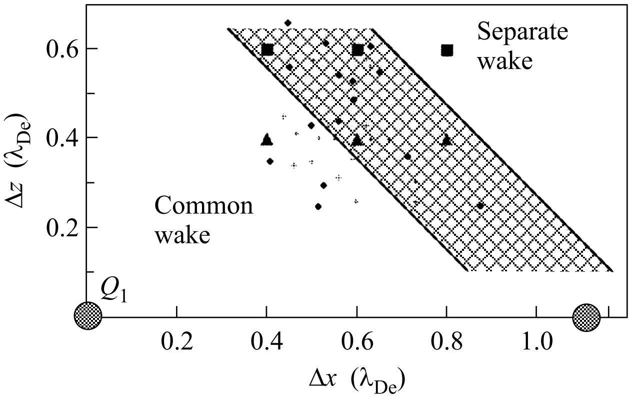

Fig.4. The symmetry-breaking diagram for the experimentally observed disruption points (crosses stand for $P = 30\,\mathrm{mTorr}$ and the input power $W = 40\,\mathrm{W}$; circles stand for $P = 50\,\mathrm{mTorr}$ and $W = 40\,\mathrm{W}$; diamonds stand for $P = 50\,\mathrm{mTorr}$ and $W = 60\,\mathrm{W}$). The MD simulation points are represented by the large squares and triangles. The grey area stands for those particle separations where the common ion wake appears according to the MD simulations

ence of the dust particle separation on the ion focusing including the strongly nonlinear phenomenon of the common wake formation. The discussed symmetry-breaking disruption can be considered as a self-organized transition illustrating the fundamental intrinsic property of a dust structure in a plasma as a self-organized open system. Indeed, by changing the dust-subsystem characteristics, such as the interparticle distance, we inevitably change the ambient plasma characristics, such as the ion wake focus, which in turn can crucially affect the dust subsystem properties (e.g., the positions of the particles) leading to its transition to another ordering state.

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1. H. Thomas and G. Morfill, Nature (London) **379**, 806 (1996).
2. R. L. Merlino and J. A. Goree, Phys. Today, p. 32 (July 2004).
3. V. E. Fortov et al., Phys. Uspekhi **47**, 447 (2004).
4. S. V. Vladimirov, K. Ostrikov, and A. A. Samarian, *Physics and Applications of Complex Plasmas*, Imperial College, London, 2005.
5. A. Melzer et al., Phys. Rev. Lett. **83**, 3194 (1999).
6. V. Steinberg et al., Phys. Rev. Lett. **86**, 4540 (2001).
7. S. V. Vladimirov and A. A. Samarian, Phys. Rev. E **65**, 046416 (2002).
8. A. M. Ignatov, Plasma Phys. Rep. **29**, 296 (2003).
9. A. A. Samarian, S. V. Vladimirov, and B. W. James, Phys. Plasmas **12**, 022103 (2005).
10. S. V. Vladimirov and M. Nambu, Phys. Rev. E **52**, 2172 (1995).
11. K. Takahashi, T. Oishi, K. Shimonai et al., Phys. Rev. E **58**, 7805 (1998).
12. D. Winske, W. Daughton, D. S. Lemmons, and M. S. Murillo, Phys. Plasmas **7**, 2320 (2000).
13. M. Lampe, G. Joyce, and G. Ganguli, Phys. Plasmas **7**, 3851 (2000).
14. S. V. Vladimirov, S. A. Maiorov, and N. F. Cramer, Phys. Rev. E **67**, 016407 (2003).
15. S. V. Vladimirov, S. A. Maiorov, and O. Ishihara, Phys. Plasmas **10**, 3867 (2003).
16. N. Goldenfeld, *Lectures on phase transitions and the renormalization group*, Addison-Wesley, Reading, Massachusetts, 1992.
17. F. A. Jenkins and H. E. White, *Fundamentals of Optics*, McGraw-Hill, New York, 1976.
18. S. A. Khrapak, A. V. Ivlev, G. E. Morfill, and S. K. Zhdanov, Phys. Rev. Lett. **90**, 225002 (2003).
19. S. A. Khrapak, V. N. Tsytovich, A. Ivlev et al., Phys. Rev. Lett. (2005), in press.