Dynamics of motion of particles with a modified surface in a dusty plasma monolayer

M M Vasiliev\textsuperscript{1,2}, E A Kononov\textsuperscript{1,2}, K Arkar\textsuperscript{1,2} and O F Petrov\textsuperscript{1,2}

\textsuperscript{1} Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia
\textsuperscript{2} Moscow Institute of Physics and Technology, Institutskiy Pereulok 9, Dolgoprudny, Moscow Region 141701, Russia
E-mail: gadvin@yandex.ru

Abstract. The results of the analysis of the mean square displacement and the trajectories of moving polymer particles with a modified surface in a dusty plasma monolayer under the influence of laser radiation are presented. It has been revealed that the dynamics of particle motion in a monolayer consists of three modes: finite motion within confinement, Brownian motion, and combined directional chaotic motion. The results of the analysis of linear displacement along and across the direction of motion of dust particles at various values of the laser radiation power are presented too. It has been shown experimentally that polymer particles with a modified surface are active Brownian particles and their activity grows with increasing laser radiation power.

1. Introduction
Over the past decade, the investigation of active matter has become one of the most exciting and rapidly developing new directions in the physics of soft matter, as well as statistical mechanics and materials science [1–4]. Active matter is a new and very complex object. Active particles are able to convert autonomously an available environmental energy (chemical, electromagnetic, thermal, etc) into their own mechanical motion. Synthetic active particles, as a rule, consist of composite materials whose components interact differently with the medium or have a different response to external disturbances. Regardless of the nature of its origin, the system of active particles is far from thermodynamic equilibrium. The study of phenomena associated with phase transitions in such systems, including dusty plasma structures of active Brownian particles, is a topical subject that allows us to study the evolution and self-organization of strongly non-ideal dissipative systems.

A quasi-two-dimensional dust structure in a high-frequency capacitive discharge is an easy-to-analyze and clearly arranged object for studying the relationship between the modification of dust particles, their dynamics, and the evolution of a system of such particles [5,6]. Earlier in [7], a crystal-liquid phase transition in a monolayer of modified particles in plasma of a capacitive high-frequency discharge was experimentally observed after exposure. An explanation of the phase transition is proposed taking into account the role of the photophoretic force acted to the macroparticles. A further study of the nature of the motion and activity of the macroparticles in such a system at a nonequilibrium phase transition is of undoubted interest.
Figure 1. The trajectories of particles with a modified surface in the plane of the monolayer recorded during 1 s for various values of the laser radiation power: (a) $W_{\text{las}} \approx 0.6 \text{ W}$, $\Gamma^* \approx 550$; (b) $W_{\text{las}} \approx 0.8 \text{ W}$, $\Gamma^* \approx 500$; (c) $W_{\text{las}} \approx 1.4 \text{ W}$, $\Gamma^* \approx 150$; (d) $W_{\text{las}} \approx 1.9 \text{ W}$, $\Gamma^* \approx 90$; (e) $W_{\text{las}} \approx 3.1 \text{ W}$, $\Gamma^* \approx 40$; (f) $W_{\text{las}} \approx 7.2 \text{ W}$, $\Gamma^* \approx 10$.

2. Experiment and results

The experiment was carried through in plasma of a capacitive high-frequency discharge formed between two disk-shaped steel electrodes. For injection of dust particles and video recording of processes taking place in the discharge, there is a hole made in the center of the upper electrode. An alternating voltage from a high-frequency generator was applied to the electrodes, resulting in a high-frequency discharge.

Argon was used as the plasma-forming gas. During the experiment, the gas-discharge chamber was continuously pumped out by a turbo-molecular pump, and the working pressure in the chamber was maintained by the continuous supply of buffer gas. Thus, the discharge plasma remained constant composition and properties throughout the experiment.

In the experiment, monodisperse spherical polymer particles of melamine-formaldehyde with a diameter of $10.60 \pm 0.12 \mu\text{m}$ and a density of 1.5 g/cm$^3$ were used to form a two-dimensional dusty plasma structure. The formed plasma crystal contained $\approx 1500$ particles and was confined in the field of the trap ring. For visualization, the resulting structure was highlighted by an argon gas-discharge laser beam which formed a “laser knife”. During the experiment, after 90 min of exposure to the dust structure in the discharge, the laser radiation power gradually increased every 4 min up to 7.18 W.

The observed change of the particle movement patterns and the evolution of the dust system due to an increase in the power of laser radiation, was recorded by a MotionPro high-speed video...
camera with a frame rate of 200 fps. Computer processing of the obtained experimental videos allowed us to get data about the evolution of the dust subsystem under the influence of laser radiation, namely the coordinates of the particles for each moment of time, their trajectories and velocities, as well as the mean square displacements and linear displacements along and across the velocity vector of dust particles. Earlier in [7], the degree of ordering (the correlation function and the effective coupling parameter $\Gamma^*$ [8]) of the dusty plasma structure was determined. Figure 1 shows the trajectories of modified dust particles in the plane of a monolayer during 1 s under exposure of laser radiation with various values of power.

In order to analyze the patterns of motion of the modified particles, we plotted a dependence of the mean square displacement $\langle r^2 \rangle$ of macroparticles in a monolayer after exposure on time for various values of laser radiation power (figure 2). It was experimentally found that an increase in the power of the laser radiation acting on a monolayer of modified particles of melamine-formaldehyde leads to an increase in the mean square displacement of moving dust particles, which means a decrease of charged particle interaction in a monolayer.

At the same time, for the crystalline state of the dusty plasma structure at low ($< 1.4$ W) laser radiation power, there is limited movement of dust particles observed over a long period of time ($t > 0.5$ s), which can be explained by the formation of an electrostatic trap due to the strong interaction of dust particles [9]. It means that with an increase of the power of laser radiation ($> 1.4$ W), the modified particles acquire an additional impulse, allowing movement in the plane of the monolayer. At this, the diffusion of dust particles in a monolayer for short times ($t < 0.2$ s) is abnormally high $\langle r^2 \rangle = 2Dt \propto t^2$ and $\propto t^{3/2}$, where $\langle r^2 \rangle$ is mean square displacement of particles, $D$ is a diffusion coefficient, $t$ is a time during which a shift occurs, which corresponds to the ballistic and transitional regimes of anomalous diffusion. However, for large times ($t > 0.2$ s) the experimental data are consistent with normal diffusion.
\[ \langle r^2 \rangle = 2Dt \propto t. \]
Thus, the dynamics of the movement of the modified particles of melamine-formaldehyde in the monolayer changes at different laser radiation powers and exhibits three patterns: finite motion within confinement, Brownian motion, and combined directional-chaotic motion consisting of laser-induced (photophoresis) and Brownian motion, which is consistent with the observed trajectories of the dust particles.

To analyze the activity of the modified polymer particles, we constructed the dependence of the linear displacement inside the Brownian motion of particles along and across the direction of motion on different values of the laser radiation power (figure 3). One can see that with an increase in the power of the laser radiation acting on the dusty plasma monolayer, the linear displacement along the direction of motion of the particles grows, while the linear displacement across the direction of motion of the particles remains constant and equal to 0 within the error.

So, according to the definition of active Brownian particles [1], we consider that modified particles of melamine-formaldehyde in a monolayer after 90 min of exposure in a plasma of a capacitive high-frequency discharge start exhibiting an activity when exposed to laser radiation, as revealed by analysis of their mean square displacement and trajectories.

3. Conclusion
A change of the motion patterns of polymer particles with a modified surface in a dusty plasma monolayer with a growth of the power of the laser radiation was observed. The analysis of the trajectories and the root-mean-square displacements of the macroparticles in the monolayer showed a different dynamics of the motion of the macroparticles at different laser radiation powers: when the laser radiation power was less than 1.4 W, the particles were trapped; when the laser radiation power was more than 1.4 W, the Brownian motion and the combined directional chaotic motion, consisting of laser-induced (photophoresis) and Brownian motion took place.

**Figure 3.** Linear displacement \( L \) during Brownian motion of particles with a modified surface along and across the direction of motion for various values of the laser radiation power \( W_{\text{las}} \): circles—linear displacement along the direction of movement; squares—linear displacement across the direction of movement.

\[ \Gamma^* \approx 550 \]
\[ \Gamma^* \approx 150 \]
\[ \Gamma^* \approx 90 \]
\[ \Gamma^* \approx 40 \]
\[ \Gamma^* \approx 10 \]
An analysis of the linear displacement along and across the direction of motion of the particles at different values of the laser radiation power showed that particles with a modified surface exhibited activity when exposed to laser radiation and their activity grew with increasing power of the laser radiation. We consider that the evolution of a quasi-two-dimensional dusty plasma structure of polymer particles with a modified surface turned out to be possible because the particles acquired the properties corresponding to active Brownian ones. The mechanism of converting laser radiation energy into motion energy, which appeared as a result of surface modification, allowed polymer particles to change the dynamics of their motion and the degree of their activity depending on the power of the acting laser radiation, which led to a phase transition in the dusty plasma monolayer.

Acknowledgments
This study was supported in part by the Russian Foundation for Basic Research (project No. 18-38-20175).

References
[1] Bechinger C, Di Leonardo R, Löwen H, Reichhardt C, Volpe G and Volpe G 2016 Rev. Mod. Phys. 88 045006
[2] Ginot F, Theurkauff I, Levis D, Ybert C, Bocquet L, Berthier L and Cottin-Bizonne C 2015 Phys. Rev. X 5 011004
[3] Uspal W E, Popescu M N, Dietrich S and Tasinkevych M 2015 Soft Matter 11 434–8
[4] Fodor E, Nardini C, Cates M E, Tailleur J, Visco P and van Wijland F 2016 Phys. Rev. Lett. 117 038103
[5] Fortov V E, Khrapak A G, Khrapak S A, Molotkov V I and Petrov O F 2004 Phys. Usp. 47 447–92
[6] Vaulina O S, Petrov O F, Fortov V E, Khrapak A G and Khrapak S A 2009 Dusty Plasma: Experiment and Theory (Moscow: FIZMATLIT)
[7] Kononov E A, Vasiliev M M and Petrov O F 2018 J. Exp. Theor. Phys. 153 721–5
[8] Vaulina O S and Dranzhlevskii I E 2006 Phys. Scr. 73 577–86
[9] Knapek C A, Samsonov D, Zhdanov S, Konopka U and Morfill G E 2007 Phys. Rev. Lett. 98 015004