External rotating electric fields make it possible to induce long-range and many-body tunable interaction between particles of colloidal systems. Moreover, such a system can be visualized in real time with the spatial resolution of individual particles. The interaction is controlled according to the following mechanism [1-4]: the external rotating electric fields induce and modulate anisotropic interactions between them, but the rotation of the field in the plane of the system leads to the appearance of anisotropic tunable dipolar attraction at large distances [1-4]. External rotating electric fields make it possible to carry out various manipulations with different types of particles of colloidal suspensions, including biological objects. The ability to control interactions between biological cells and carry out their self-assembly in external rotating electric fields [5] can be applied in novel diagnostic methods, in the lab-on-chip or organ-on-chip concept, in 3D-imprinting technologies.

In addition to promising applied applications, colloidal systems in external rotating electric fields are an excellent model system for studying fundamental phenomena. In a monolayer of colloidal particles with interactions tuned by the external rotating electric field, interactions and phase transitions were studied. Experiments and molecular dynamics (MD) simulations allowed to demonstrate that the system represents a unique platform for studying the effects of long-range and many-body interactions and phase transitions in liquids and solids. The use of such a system opens the way to establishing the role of strong many-body forces in the dynamics of colloids, melting, domain dynamics in polyelectrolytes, diffusion, gelation and coagulation of gels, interphase phenomena, and the kinetics of phase transitions.

Colloidal suspensions with interactions tuned by the external rotating electric fields can also be used as model systems for the experimental verification of various hypotheses and methods. In particular, for the first time the experimental verification of the Interpolation Method (IM) was carried out for pair correlations functions in model crystals. Crystallographic structures are widespread in nature, both living and non-living. Therefore, understanding the processes occurring in crystal structures is important both from the point of view of studying fundamental phenomena and from the point of view of applied applications. Colloidal suspensions and complex (dusty) plasmas were used as model systems, allowing experimental studies of particle resolution with tunable interactions and providing a perfect test platform for thorough analysis of pair correlation using IM [8-12]. Experiments were carried out with charge-stabilized 3D colloidal crystals in neon-solvent, with 2D colloidal crystals (dusty particles in demineralized water), and with 2D complex (dusty) plasma crystals. These systems provide a unique opportunity to study model crystals with a wide range of particle interactions - from soft to hard spheres - with spatial resolution of individual particles.

**ABSTRACT**

The interactions and phase transitions in a monolayer (2D) colloidal system with in situ tunable interactions induced by in-plane rotating electric field.

**Experimental setup**

**Schematic representation of experimental setup for tunable self-assembly of colloidal particles in external rotating electric field.** Panel (a) presents a general scheme of the setup with details shown in (b), panel (c) is a photo of eight-electrodes cell made by lithography, distance between annulus 300 μm.

**Schematic illustration of interactions tuned by an external electric field.** Colloidal crystals from 3D colloidal suspensions can be tuned by external electric fields, shown in panel (a), locally, is controlled by respectively charged particles. Applied external electric field polarizes colloidal in panel (b). After polarization, the particles start to interact between each other by dipole-dipole interaction. Since the field rotates at a high frequency in the particle system between particles attraction, repulsion.

**Phase diagram of collisional suspension with tunable interactions in rotating electric field.** (a) phase diagram with the critical and triple points (CP, TP). (b) parameter $\mu$ characterizing fluctuations of the Normal distribution in colloidal and liquid clusters, in the snapshots of the typical crystalline, liquid, and gaseous states of the colloidal system in different points $\lambda P$ shown at the phase diagram.

**The mapping of three-body tunable three-body energy in charged colloidal particles.** The solid red line is the profile of tunable three-body energy of triangular triple with distance in our system at $\phi_{cr} / \phi_c = 0.5$. The dashed orange line is the fit of the three-body energy in rotating electric field by the energy of triple calculated within framework Pitzer-Boukhalim (PB) theory, in $\nu = 1.4$ corresponding to the screening $\kappa = 2.5$.

**The interactions and phase transitions in a monolayer (2D) colloidal system with in situ tunable interactions induced by in-plane rotating electric field.**

**Experimental validation of interpolation method for pair correlations in model crystals**

An illustration of the IM in a 2D hexagonal lattice. The origin of the coordinate system is placed at the base of a particle, other particles move around their equilibrium positions (in this coordinate system) the lattice nodes $\phi$, with corresponding radial vectors shown by the gray arrows.

The 3D colloidal crystals created with 1.6 μm diameter PMMA particles. The 2D plane of a 3D colloidal crystal is the plane of the sheet of crystals, which can be observed through TEM (Transmission Electron Microscope) image of an individual PMMA particle.

**Pair correlation functions in 3D colloidal crystals:** (a) and (b) pair correlation functions $g(r)$ obtained experimentally (blue symbols) and with body-integrated fits with BD (solid orange line) for two colloidal crystals with $a_{col} = 2.0$ (volume fraction $\phi = 0.101$, interparticle distance $d = 2.5 \mu m$, coupling parameter $\Gamma$, and) and $\phi_{cr} = 0.5$ (volume fraction $\phi = 0.127$, interparticle distance $d = 2.9 \mu m$, coupling parameter $\Gamma = 1301$, respectively). The means show a close-up of the experimental sections in the crystal of the Yukawa system (grey symbols and lines). Blue triangles are results based on the theoretical estimation of the particle charge $z$, orange diamonds are the points obtained using the proposed fitting of (g(r)) with IM. Labels $a$ and $b$ corresponds to the panels (a) and (b).

**The snapshot of 2D crystals under experimental study** (a) hexagonal 2D colloidal crystal of 0.2 μm diameter silica particles and (b) scaled 2D colloidal complex (dusty) plasma crystal of 0.19 μm MP particles in plasma discharge.

**Pair correlation functions in 2D crystals:** (a) and (b) pair correlation functions (g(r)) in the studied colloidal crystal $\phi_{cr} = 1.0 \%$, for (a) solid orange line theoretical fits of $\mu(r)$ with BD, while the insets show close-ups of the first correlation peaks. (b) and (d) present in color-code format the peak $\mu(r)$ corresponding to nearest-neighbor in colloidal and complex (dusty) plasma crystal, respectively. Black contours are experimental isolines of $\mu(r)$, red contours correspond to the isolines of theoretical fit $\mu(r)$ with IM.

**The effect of many-body interactions on the pair correlation function.** The pair correlations functions observed in the bi-crystals with many-body interactions. The solid red line is the IM predicted (a) pair correlation functions in the model systems with the nearest-neighbor exclusion. The inset shows a close-up of the first correlation peak. This system is suitable to 1) the form of g(r) with some effective parameters.

**REFERENCES**