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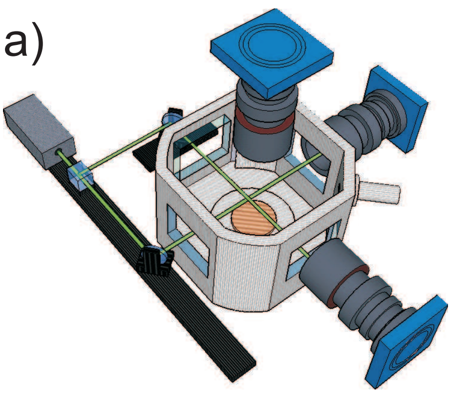
Normal Mode Dynamics of Yukawa Balls

Y. Ivanov, A. Melzer

Institut für Physik
Ernst-Moritz-Arndt-Universität Greifswald, Germany

Finite dust clusters consist of a small number of dust microspheres N immersed in a gaseous plasma environment. Recently, the formation of spherical 3D clusters, so-called Yukawa balls, has been achieved by special discharge configurations [1]. There, the particles of the Yukawa ball macroparticles form an "onion" shell structure. Within each shell they form a hexagonal structure with some 5-fold defects due to the curvature of the shell surface. The Yukawa ball is confined in a weak recombining plasma which makes direct measurements of the plasma parameters difficult. Thus, the indirect measurements are needed.

In this paper, we will focus on the dynamics of Yukawa balls. We will calculate the normal modes and assess with their help the basic system physical parameters: the particle charge Q_d and the confinement strength (a free oscillation frequency of a single particle in a confinement) ω_0. The experimental setup is analogous to the one used in [1]. The experiments have been performed in an asymmetric capacitively coupled rf-discharge operated in argon at 13.56 MHz. 3.47 μm in diameter plastic spheres have been dropped into a plasma from a "salt shaker" at the top of the plasma chamber. The schemes of the experimental setup and the confinement of a Yukawa ball are presented in Fig. 1. A square glass box on the lower electrode forms the plasma profile and provides the lateral confinement for the enclosed dust



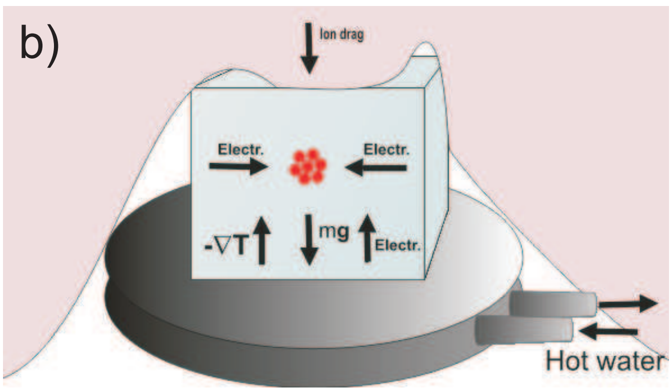


Figure 1: a) Scheme of the experimental setup. b) Yukawa ball confinement scheme.

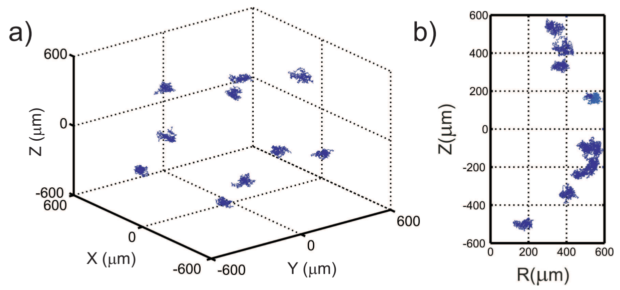


Figure 2: a) 3D particle trajectories in the 10-particle Yukawa ball b) Radial diagram (vertical dust particle coordinate (Z) vs. radial horizontal position ($\sqrt{X^2+Y^2}$)) of the same trajectories showing one-shell structure.

cloud. The particles are trapped in the center of the glass box where the plasma-induced electric field force together with a thermophoretic force levitates the microspheres against the gravity.

Three high-speed synchronised cameras were placed under right angle to each other. Trajectories of dust particles constituting a Yukawa ball are observed and recorded here with the help of this stereoscopic system. Unlike 2D systems where only one CCD camera is applied, the study of Yukawa Ball dynamics is more complicated due to the need to use two or three CCD cameras [2]. This increases a potential error of reconstructed dust particle coordinates due to the necessity of identifying corresponding particles in different cameras and taking into account calibration camera errors. For normal mode analysis, this reconstruction error should be smaller than a characteristic length of thermal particle motion, therefore an accurate coordinate retrieving method has to be applied ([3]). However, the experimental investigation of thermal motion of Yukawa Ball particles is of great interest because it allows to investigate low frequency normal modes. Normal modes provide an indispensable diagnostic of cluster dynamics successfully studied earlier e.g. in 2D dust crystals [4].

We will discuss here experiments on a Yukawa ball with 10 microparticles. In Fig. 2 the one-shell structure of this Yukawa ball is presented. The reconstructed trajectories of the 10 particles are presented in Fig. 2(a). The thermal particle fluctuations are clearly seen here. The normal modes are obtained as the solution of the eigenvalue problem for the dynamical matrix ([4]):

$$A_{\alpha\alpha',ij} = \frac{\partial^2 E}{\partial r_{\alpha,i}\partial r_{\alpha',j}}, \qquad E = \frac{1}{2}m\omega_0^2\sum_{i=1}^{N} r_i^2 + \frac{Z^2e^2}{4\pi\epsilon_0}\sum_{i<j}^{N}\frac{\exp(-r_{ij}/\lambda_\mathrm{D})}{r_{ij}},$$

where E is the cluster potential energy. $r_i = |\vec{r}_i|$ here is the distance of the ith particle from the center of the confinement and $r_{ij} = |\vec{r}_i - \vec{r}_j|$ is the distance between the particles i and j. For the 3D case $r_{\alpha,i}$ stands for the x, y and z coordinate of the ith particle and the pairs α, α' consecutively number all possible pairs from these coordinates.

The eigen values and eigen vectors of the dynamical matrix describe the normal mode oscillations of the finite clusters. The eigen values are the oscillation frequencies and the eigen vectors describe the mode oscillation patterns. There are $3N$ normal modes in a Yukawa ball of N particles.

Experimentally, the normal mode spectra are obtained from the Fourier transform of the projected particle velocities in mode number $\ell = 1 \ldots 3N$ by (see e.g. [4] for details)

$$S_\ell(\omega) = \frac{2}{T} \left| \int_0^T v_\ell(t) e^{i\omega t} \right|^2 \quad .$$

Here, $v_\ell(t) = \sum_{i=1}^N \vec{v}_i(t) \cdot \vec{e}_{i,\ell}$ are the projections of Brownian particle fluctuations with velocities $\vec{v}_i$ around their equilibrium positions onto the normal mode patterns $\vec{e}_{i,\ell}$ of the mode ℓ. Three chosen normal modes, the ”breathing” mode, rotation and one of three sloshing modes, of the 10-particle crystal are shown in Fig. 3(a-c). These modes are the natural extension of corresponding 2D normal modes to the 3D case. The rotation and the sloshing mode frequencies are independent on the screening length λ_D. For pure Coulomb interaction in a 3D cluster the frequency of the breathing mode is $\omega = \sqrt{3}\omega_0$. With increasing screening of dust particles by an ambient plasma the frequency of the breathing mode in Yukawa ball also increases.

The spectral power density $S_\ell(\omega)$ of the 10-particle Yukawa ball is shown in Fig. 3(d). The confinement strength ω_0 is found from the fit of the theoretical normal mode frequencies (shown as black circles) to the experimental mode spectrum. From that the confinement strength was obtained as $\omega_0 = 1.9s^{-1}$. Then, the particle charge is obtained, as $Q_d = 1500e$. This result is in best agreement with the results from recent experiments ([5],[6]) and calculations. The experimental spectrum power is isotropically distributed within the three experimental sloshing modes (not shown in the figure). This confirms the isotropy the confinement potential.

Summarizing, the trajectories of dust particle forming a 3D finite Yukawa ball have been experimentally determined with high enough accuracy for the normal mode analysis. The

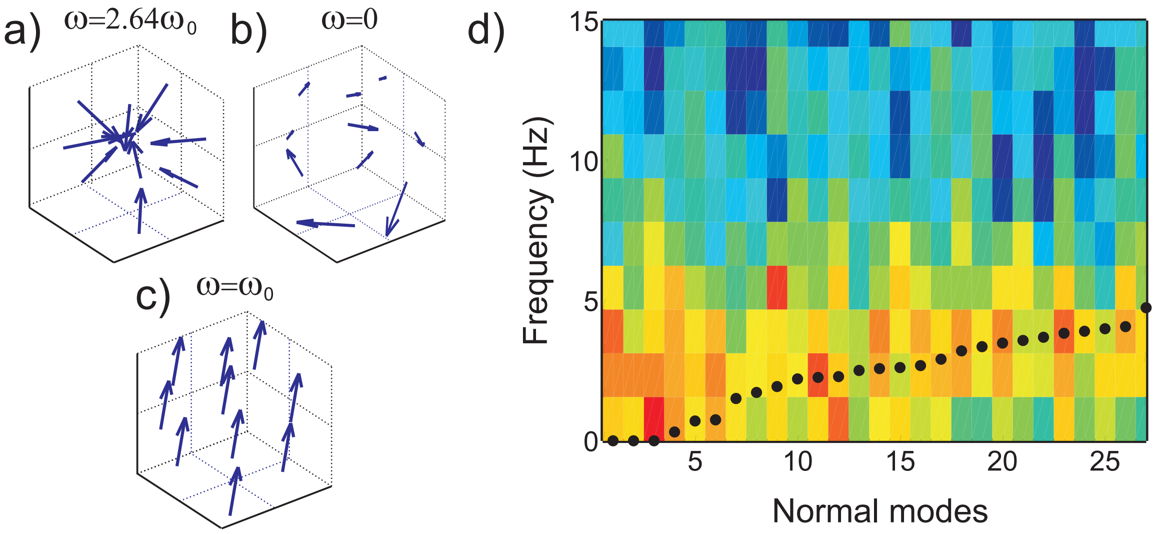


Figure 3: The normal mode patterns and the power spectrum of the 10-particle Yukawa ball: a) the ”breathing” mode, b) rotation and c) one of three sloshing modes. The numbers are the corresponding normal mode frequencies ω in the units of the confinement strength ω_0. d) power spectrum of the 10-particle crystal. Black circles stand for the theoretical normal mode frequencies.

experimental normal modes have been calculated and investigated. The main physical parameters, the particle charge and the confinement strength, were determined. The found parameters are in a very good agreement with other experimental results.

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