Rectified transport in chains of paramagnetic colloids driven over garnet film

Dr. P. Tierno has recently developed a method to experimentally transport paramagnetic colloids over the surface of a uniaxial ferrite garnet film [1]. The method was based on a deterministic ratchet effect resulting in a synchronized directed motion of colloids above the frequency-modulated magnetic landscape. To move the particles he utilized a rotating magnetic field with elliptic polarization. In particular, it was found that for certain field parameters the particles assembled into traveling chains or "colloidal trains," showing enhanced transport.

The aim of the short visit of Dr. A. Straube to the group of Dr. P. Tierno was to start a systematic study of the mechanism of train formation, both theoretically and experimentally. We divide the planned activity into three parts: i) The dynamics of a single paramagnetic particle driven above a garnet film and subject to an external rotating field; ii) The interaction of two paramagnetic particles induced by an elliptically polarized external field; iii) Collective effects including qualitatively different dynamic phases composed of moving crystals or trains depending on the ellipticity of the rotating field. The first part of the program, including new measurements, has been fully completed and we are preparing a first joint publication. The second part is in progress after the visit, which will be followed by simulations in the third part.

First, we have considered the motion of a single paramagnetic colloid for the case of circular polarization of the external field. As already expected from preliminary experimental data and results of simulations, the dependence of the averaged speed of a colloid on the frequency shows a transition between two nonequilibrium states. One in which the particle motion is fully synchronized with the magnetic potential (low frequencies) and the second in which the motion becomes desynchronized and the particle displays a sliding dynamics characterized by a lower speed (high frequencies). Up to now, the dynamics of a particle has been induced by a linearly oscillating field and described numerically by solving an equation for the particle in garnet film potentials, as suggested earlier [1, 2]. These potentials have a complex form obtained by using conformal mapping technique to determine the field above the substrate, which substantially increases the complexity of the problem. Remarkably, during the visit we managed to obtain a very simple and accurate approximation of the potential (Fig. 1), which allowed for an analytically tractable model. We showed that the problem can be reduced to a stochastic Adler equation [3] and obtained analytic expressions for the critical frequency, the averaged speed as a function of frequency, see Fig. 1(d), and the distribution of particle positions.

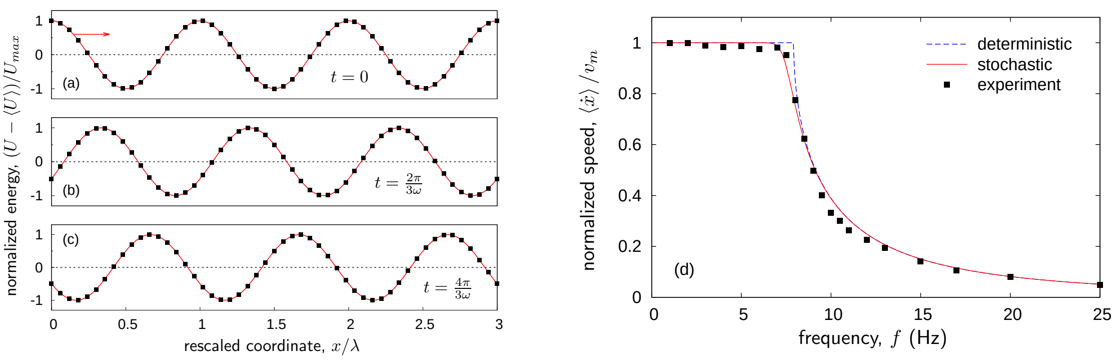

Figure 1: Comparison of the normalized energy potential evaluated from the complex solution (markers) and from a simplified expression plotted as a function of the coordinate x at three different fractions of period, $t = 0$ (a), $2\pi/(3\omega)$ (b), and $4\pi/(3\omega)$ (c). Comparison of the experimental (markers) data and analytical predictions (lines) for the normalized speed as a function of frequency f (d). The dashed and solid lines show the theoretical predictions without and with thermal fluctuations, respectively.

At the moment we are extending this model to the case of the external field of elliptic polarization, for which the similar simplified potential is as accurate as for the circularly polarized field. By tuning the value of the ellipticity parameter, we can achieve either repulsive or attractive interactions. Here we systematically study the interactions between two particles. Although for the case of nonzero ellipticity the problem is no longer analytically tractable, the idea is to obtain effective time-averaged equations for the case of high frequencies in one dimension and no thermal noise. In the case of noninteracting particles, the results are in agreement with the analytical solution for a single particle taken in the limit of high frequency. Further, we introduce dipole-dipole interactions between a pair of particles and treat the strength of interaction as a small parameter. As a result, we are arrive at a pair of relatively simple equations which describe the position of the center of mass and the distance between the two particles. This theory is being checked against numerical simulations, in which we can easily account for thermal fluctuations and consider particles on a plane, two-dimensional problem. Afterwards we will combine the theory with the experiment, which completes the second part.

In the future we plan to consider the case of many particles, to address collective effects, including train formation. Here, one has to take care of generally long-range dipole-dipole interactions. To be able to replicate experimental conditions, we will need to simulate a few hundreds of particles in a domain with periodic boundary conditions, which becomes computationally intense when evaluating all the interactions directly. One option would be applying the Ewald summation technique. However, our estimates show that we can stick to a much more efficient alternative. Because the dipole-dipole interactions between the particles are small in comparison with the interactions of particles with the field of the garnet film, for each colloid it is enough to account for its nearest neighbors within a range of only few particle's diameters.

Apart from the work on the project, A. Straube gave a presentation ("Mesoscopic phenomena in complex fluids and chemically reacting systems: from stochastics to pattern formation") of his recent research activity for members of the hosting department followed by a number of stimulating discussions.

In conclusion, the visit of A. Straube to the group of P. Tierno has been fruitful and productive. The results obtained during the visit are novel and interesting and are being prepared for a first publication. We consider this outcome as a successful and promising starting point for a deeper work focussing on collective effects and for a long-term collaboration between the groups.

References

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