Probing Capillary Torque on Multipolar Particles at Dynamically Deformed Liquid Interfaces

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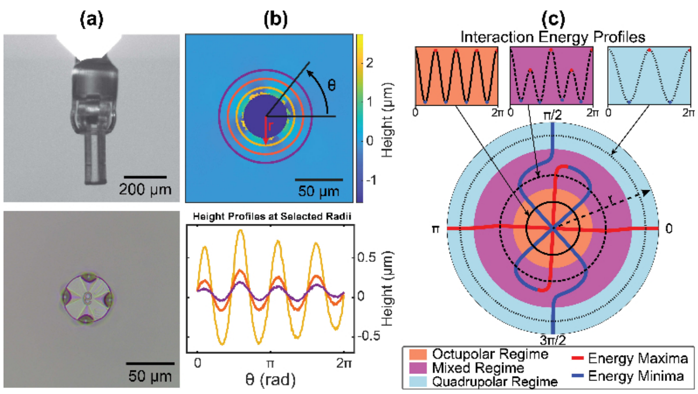
We present a novel experimental platform for probing dynamic capillary interactions at liquid interfaces through the controlled coupling of externally imposed curvature to particle-induced interfacial multipoles. At the core of our platform is a self-aligning micropillar fabricated by two-photon-lithography (Figure (a), top), which pins the liquid interface to its circumference, creating a global interfacial deformation. The micropillar is mounted on a three-axis automated stage connected to a force sensor, allowing for precise control over both the position and extent of liquid deformation, while simultaneously recording forces. Integrated with a digital holographic microscope, our platform also enables real-time monitoring of the local interface undulations around pinned particles as well as the global interfacial deformation generated by the pillar.

Using this platform, we study two-photon-lithography-printed microparticles with tailored capillary multipoles (Figure (a), bottom) and quantify their response to a dynamically imposed monopolar interface deformation. From measured height fields, we extract the multipolar capillary charges of the particles (Figure (b)) and the monopolar charge of the micropillar. We use these quantities to determine the distance- and angle-dependent capillary energy landscape (Figure (c)) and the capillary torque driving particle reorientation. Because the capillary torque exhibits a slower radial decay than the capillary force, we can isolate particle reorientation in a regime of weak translation and quantify its dependence on particle-micropillar separation. Specifically, we identify a near-field regime governed by the particle's multipolar geometry, a far-field regime dominated by a more slowly decaying quadrupolar mode, and an intermediate regime in which several capillary modes contribute simultaneously (Figure (c)). We show the angular trajectories follow the predicted relaxation toward local energy minima and can be used to extract an effective rotational mobility. The ability to create and visualize controlled liquid deformations broadens our understanding of particle behaviour at liquid interfaces beyond static interfaces and opens new avenues for exploring particle dynamics in complex, dynamically evolving liquid topographies.

Keywords:
Capillary Torque, Rotational Dynamics, Liquid Interfaces



(a) Brightfield images of a mounted micropillar (top) and an octupolar particle at a water-oil interface (bottom), (b) height field measurement (top) of the particle with extracted azimuthal profiles (bottom). (c) Modelled capillary energy landscape based on experimental octu- and quadrupole values.

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