FIG. 1. (Color) (a) Scanning electron micrograph of an amphiphilic, ferromagnetic microdisk ($20\ \mu\text{m}$ diameter) with $5\ \mu\text{m}$ diameter buttonholes. (b) Schematic of a ferromagnetic microdisk probe at the water-DPPC-air interface and (c) bright-field image of an oscillating microdisk with tracked buttonholes. (d) Fluorescence micrograph of a microdisk within a liquid-condensed DPPC monolayer. (e) Steady disk rotations ($60\ \text{Hz}$) partition the interface into two separate regions: a flowing region around the microdisk, and a steadily deformed elastic region farther away (scale bar: $20\ \mu\text{m}$).

Dynamics within surfactant monolayers

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(Received 3 September 2010; published online 30 September 2010)
[doi:10.1063/1.3492833]

Water-air interfaces are seldom clean, and frequently host monolayers of surface-active (“surfactant”) molecules. In lowering interfacial energy (surface tension), surfactants play key roles in enhanced oil recovery and in mixing, blending, and stabilizing multiphase materials. Surfactant soaps keep us clean, and surfactant monolayers allow us to breathe.

Despite their molecularly thin nature, surfactant films can have a profound influence on the behavior of free fluid surfaces. Additionally, molecules within the monolayer can form *ordered* phases, yet still flow like two-dimensional liquids. Properly visualized,¹ such monolayers can reveal extraordinarily beautiful structures.

We investigate the flow response of the phospholipid surfactant dipalmitoylphosphatidylcholine (DPPC), which is a significant component of our lung surfactant monolayers, as well as our cells’ lipid bilayers. We microfabricate micron-scale ferromagnetic, amphiphilic disks [Fig. 1(a)], which we place on a water-DPPC-air interface [Fig. 1(b)] and torque with external electromagnets [Fig. 1(c)]. Notably, we can visualize the interface directly while we torque the disk.

Figure 1(d) shows a disk within a DPPC monolayer in the liquid-condensed (LC) phase, which consists of a packed layer of individual, $10\ \mu\text{m}$ -scale grains, each of which contains a two-dimensional fluid with liquid-crystalline orientational order. The grain structure is visualized with a small fraction (0.1 mol. %) of Texas red-labeled 1,2-dihexadecanoyl-sn-glycero-3-phosphoethanolamine (DHPE), which cannot pack within the liquid-crystalline domains and is thus forced to the grain boundaries.¹ Under steady disk rotation, the monolayer partitions into two distinct regions: a static outer region, where domains show a steady elastic deformation, and an inner “yielded” region, which flows freely [Fig. 1(e)]. The surface yielding behavior exhibited by the LC-DPPC monolayer is reminiscent of its three-dimensional analog, as when butter is spread.

We gratefully acknowledge primary support from the NSF through the MRSEC program (Contract No. DMR-0520415), the Beckman Young Investigator Program, the NIH under Grant Nos. HL-51177 and GM076709, the MRL Central Facilities, a member of the NSF-funded Materials Research Facilities Network, and the UCSB Nanofabrication facility, part of the NSF-funded NNIN network.

¹H. M. McConnell, L. K. Tamm, and R. M. Weis, “Periodic structures in lipid monolayer phase transitions,” *Proc. Natl. Acad. Sci. U.S.A.* **81**, 3249 (1984).