Microrheology at the Liquid-Crystal Water Boundary

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Abstract
We demonstrate the viscosity measurement using laser-trapped liquid crystal droplet. The viscosity determined experimentally depended on the diameter of the droplet and boundary conditions at the liquid crystal surface which was changed by adding surfactant.

In the fast-growing field of the nano-, micro-world research, the momentum of photons has become a tool to hold, manipulate, and characterize objects with dimensions from 10 nm to 50 μm. Laser tweezers has become a powerful tool to study the microscopic structure and micro-rheology. It has recently been demonstrated that a birefringent spherical particle of vaterite trapped by circularly polarized laser tweezers can be used to measure the viscosity of the environment in which it is spinning:

\[ \mu = \frac{P(1 - \sigma_{\text{out}}) / \omega}{8\pi r^3 \Omega}, \]  

where P is the laser trapping power at the focus, \( \omega \) is the cyclic frequency, \( \sigma_{\text{out}} \) is the polarization coefficient, and \( r \) with \( \Omega \) are the radius and spinning frequency of the laser-manipulated sphere. The change in ellipticity of the circularly polarized light of the tweezer after passing through the particle is accounted for by \( \sigma_{\text{out}} \), which can change from 0 for linearly polarized output to \pm 1 for fully left- and right-polarized light output, respectively.

Here, we show applicability limits of the proposed concept for the probing of micro-environments and demonstrate the viscosity determination using liquid crystal droplet. First, the eqn. 1 is only valid for a non-slipping boundary condition, which applies for hydrophilic surfaces. Conversely, for a hydrophobic surface, a 100 nm hopping of water molecules has been established. This results in an effectively lower viscous drag. Secondly, only the longitudinal projection of the cumulative angular momentum of the passing light spins the particle. The half-cone angle of focusing is larger than \( \pi/3 \) in standard laser tweezers. Third, the shape of laser-tweezed “soft” bio-materials can be changed due to their ductility, consequently, the rotational drag coefficient becomes different and modifies the spinning efficiency rendering, also, eqn. 1 invalid.

In order to test the proposed concept and listed precautions, we carried out a laser-tweezed spinning experiment on nematic liquid crystal droplets, which formed perfect spheres by surface tension in water. Laser-tweezers were modified to reproduce the same setup as in ref. 2. Figure 1 schematically illustrates the principle of measurement. We used the 4-pentyl-4'-cyanobiphenyl (CB5, Aldrich) and E44 (Merck) nematic liquid crystals in D2O, which has negligible absorption at 1064 nm. This excluded heating present in the reported experiments. Hence, alterations of viscosity due to rising temperatures were avoided while the sphere size and laser power dependence of the measured viscosity was tested. Each liquid crystal forms 1-10 μm droplets by self-organization with the bipolar structure when dispersed in D2O. Figure 2 summarizes experimental data showing the size and power dependences of the calculated viscosity (eqn. 1). With spheres approximately 2.5 μm in diameter, the correct value of viscosity was measured (e.g., a 2.41 μm vaterite spheroid was used in ref. 2). For larger and smaller
Viscosity

Propagation is the closest parallel to efficiency measured with hydrophobic wetting and occurred, making change carried by the beam. The most efficient angular momentum transfer occurred, making eqn. 1 appropriate.

By adding non-ionic surfactant Tween20, the measured viscosity increased. This suggests a change of liquid crystal surface and its interaction with surrounding water. In order to test whether the non-slipping boundary condition applies, we carried out the same experiment on highly hydrophobic and rigid spherical droplets of E44. Calculated by eqn. 1 viscosity was only $\mu = (0.3\pm 0.1)$ mPa·s when droplets of optimal diameter 2.3-2.5 μm were used (Fig. 3). This could be accounted for by the occurrence of slip at the D$_2$O droplet boundary, resulting in much lower viscous drag in compliance with the reported hopping of water molecules. This opens a possibility of investigate interface friction and wetting using laser tweezers.

The amount of angular momentum transfer from laser beam into the torque of the droplet can be calculated as $(1-\sigma_{rod})/2$ and is the largest when the droplet acts as a $\lambda/2$-plate. In our experiments the efficiency of light momentum harnessing was $22.5\pm 9\%$ and $11\pm 8\%$ for the CB5 and E44 droplets.

Fig. 2. Viscosity vs. laser power for different diameter spheres (CB5). Horizontal line represents viscosity of D$_2$O at 25 °C, $\mu = 1.232$ mPa·s.

In conclusion, we have demonstrated that the viscosity determination method of ref. 2 can not be used without the knowledge of actual light intensity distribution inside the microsphere and its wettability and shape. Viscosity value depends on the diameter of droplet and the condition of liquid crystal surface.

References

7) The smallest droplets were comparable with the focal size and some of light passed by. This resulted in a lower rotation frequency, $\Omega$, and an overestimated $\mu$ value. For the larger droplets part of the angular momentum of the light was lost for the internal molecular reorientation. This has changed the birefringence, thereby exaggerating the polarization coefficient, $\sigma_{rotd}$, underestimating $\mu$. 

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