Deformation of oil drops with ultra-low interfacial tensions in an optical trap

A. D. Ward and M. G. Berry
Central Laser Facility, CCLRC Rutherford Appleton Laboratory, Chilton, Didcot, Oxon., OX11 OQX, UK

C. D. Mellor
Chemistry Research Laboratory, Mansfield Road, Oxford, OX1 3TA, UK

C. D. Bain
Department of Chemistry, Durham University, South Road, Durham, DH1 3LE, UK

Main contact email address c.d.bain@durham.ac.uk

Introduction

Micron-sized emulsion droplets have been deformed with the use of multiple optical traps sited within a single droplet. Altering the relative position of the optical traps deformed a heptane-in-water emulsion droplet into different geometric shapes. The deformations arising from the interaction of picoNewton optical forces are only realised in the presence of a surfactant, such as Aerosol OT (AOT), that reduces the oil-water interfacial tension to ultralow values. The interfacial tension of the deformable droplets was determined to be ~1×10^{-6} N m^{-1}.

Results and Discussion

In general, small objects trapped with optical tweezers do not deform because the radiation pressure of the continuous wave (CW) lasers used in optical trapping is feeble compared to the Young's modulus of most solids or to the Laplace pressure within a micron-sized liquid droplet. In particular, small droplets of oil in an emulsion form and retain perfect spherical geometry in order to minimise the surface area, and hence the Gibbs free energy, for a given volume.

It has been known, however, since the experiments of Ashkin and Dziedzic 30 years ago[1] that intense, pulsed laser beams can cause measurable deformations in a planar surfaces. In this paper we describe how large deformations can be achieved in droplets of an oil-in-water emulsion with a low-power CW laser (~10^{-2} W). For this phenomenon to occur the interfacial tension at the oil-water surface has to be reduced to a value comparable with the force constant of the optical trap, which is typically 10^{-5} – 10^{-6} N m^{-1}. Since oil–water interfacial tensions are around 0.05 N m^{-1} for an alkane, the interfacial tension has to be reduced by four orders of magnitude. Such ultralow tensions are achieved by adsorption of surfactants under conditions where the emulsion is close to the microemulsion phase boundary (where the interfacial tension vanishes). For these initial experiments we prepared an oil-in-water emulsion by blending together heptane, water, salt (0.05M NaCl) and the surfactant AOT (1mM). The interfacial tension of this emulsion system has been characterised by spinning drop tensiometry[2]. A region of ultralow interfacial tension ($<3 \times 10^{-6}$ N m^{-1}) is known to exist between 20°C and 23°C. In our study, the emulsion was injected into a 100-mm deep flow cell as shown in Figure 1. Single droplets were captured near the upper surface as droplets in the emulsion started to cream. The trapped droplet was dragged vertically down into the bulk solution to be isolated from other droplets. All deformation experiments were performed at 20.0 +/– 0.5°C.

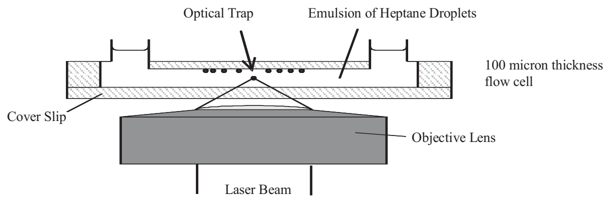

Figure 1. Schematic illustration of the flow cell used to trap emulsion droplets.

The experimental apparatus comprised a 1 W Nd:YAG laser (1064 nm), which was passed through a pair of perpendicular acousto-optic deflectors (AOD) to steer the laser beam in the x-y plane. The diffracted beam was expanded and then directed into an inverted microscope (Leica, DM-IRB) via a dichroic mirror and microscope objective (Leica, ×63 water immersion, NA = 1.2). The signals applied to the AOD were multiplexed to generate up to four optical traps with individually controllable trapping position. Laser powers at the focus were 11–27 mW. The images were recorded using a CCD camera and show the shape of the droplet as viewed in plan from beneath the sample in brightfield illumination. The measured escape force was 0.69 pN/mW, which corresponds to the maximum radial force that can be applied to a droplet in a single trap without that droplet being expelled from the trap.

Figure 2 shows an image of an oil droplet deformed symmetrically by 2, 3 and 4 traps. With a single optical trap the interfacial tension at the oil-water surface is sufficiently low that the droplet deforms into an ellipse along the axial direction of the laser beam., although this deformation is small (<20%). With two traps displaced in the focal plane, the droplet deforms into a prolate ellipsoid. On occasion, the interfacial tension is low enough that the droplet can be further extended into a dumbbell (Fig. 2). With three or four traps, the droplet adopts a triangular or square shape, respectively. In qualitative terms, these "optical sculptures" arise from photonic forces acting on the oil towards the focal points of the laser beam, balanced by a weak interfacial tension. The droplet assumes a shape of minimum surface area between the positions of the laser traps.

To estimate the interfacial tension, a droplet was deformed into an ellipsoid by a pair of traps and the maximum deformation measured at a fixed laser power. The difference between the Laplace pressure in the centre and the apex of the drop is balanced by the optical force.

From measurements of the droplet geometry we can estimate a value of the interfacial tension ~ 1×10^{-6} Nm^{-1}, which is in good agreement with the result obtained by spinning drop interfacial tensiometry.

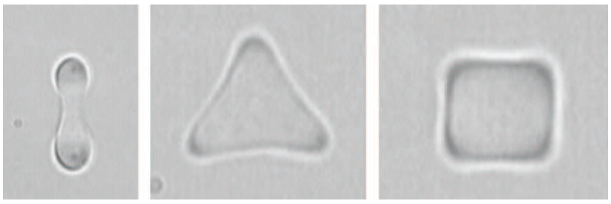

Figure 2. Shapes formed by a heptane droplet in (left) two traps, (middle) three traps in an equilateral triangle, (right) four traps in a square.

Conclusion

We have shown that the shapes of oil droplets can be controlled with optical tweezers provided that suitable surfactants are employed to reduce the oil-water interfacial tension to ultralow values (~10^{-6} Nm^{-1}). The optical traps need not be coplanar, so in principle three-dimensional control of the shape of the droplet is possible. Current work is underway to replicate these experiments with UV-curable monomers as a means of manufacturing sculpted polymeric shapes on the micron length scale.

References

1. A. Ashkin and J. M. Dziedzic, *Phys. Rev. Lett.* **30**, 139, 1973
2. R. Aveyard, B. P. Binks, S. Clark and J. Mead, *J. Chem. Soc. Faraday Trans. I,* **82**, 125, 1986