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Magnetic levitation of liquid crystals

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The principle of magnetic levitation is demonstrated using a large magnetic field gradient to elevate a polycrystalline sample of dodecyloxycyanobiphenyl against gravity. Additionally, a nematic droplet of pentylcyanobiphenyl clinging to a vertically oriented wire is elevated against gravity. The contact angle and length of the droplet are extracted from the droplet shape in the context of a gravitation-free model.

1. Introduction

Magnetic levitation (ML) of condensed systems provides a means of investigating and fabricating materials in the (near) absence of external forces. As an alternative to space-borne experiments, and of much longer duration than the typical 2–3 s drop-tube experiments, ML can be used to study a variety of material properties. In this paper we describe initial experiments on levitating a polydomain crystal of dodecyloxycyanobiphenyl (12OCB), and on the surface tension of a nematic droplet of pentylcyanobiphenyl (5CB) which clings to a fibre.

The principle behind ML is completely analogous to that used in the Faraday susceptometer. Given a material with a magnetic susceptibility (per unit mass) χ, its energy U in a magnetic field $\mathbf{H}$ is $U = -\frac{1}{2}\chi H^2$. Thus, if there exists a spatial field gradient ∇H, there is an associated force per unit mass $F_{\mathrm{magnetic}} = -\nabla U = \chi H \nabla H$. A diamagnetic material such as a liquid crystal is expelled from the region of high field, and therefore if the material is placed above a region of high field, the liquid crystal will experience an upward magnetic force. For sufficiently large $H\nabla H$, F_{magnetic} will overcome the downward gravitational force, and the liquid crystal will levitate. This effect was first demonstrated in 1939 for graphite [1], and about ten years ago at the Francis Bitter National Magnet Laboratory for water in a closed cuvette [2]. In recent years ML has been used to levitate a variety of solids and liquids, as well as biologically-relevant materials [3–6]. Owing to the small diamagnetic susceptibility χ of most materials—typically $|\chi| < 10^{-6}\,\mathrm{erg\,G^{-2}\,g^{-1}}$ for materials of density $\rho \sim 1\,\mathrm{g\,cm^{-3}}$—very large values of $H\nabla H$ are required. Most often these are obtainable only in specialized facilities or in large superconducting magnets. An additional problem is that as the divergence of the field must vanish, there also exists a radial component of force which may drive the particle away from equilibrium. These difficulties may be circumvented with a high permeability pole piece of appropriate design.

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2. Experimental set-up

In order to carry out our measurements we used a room temperature bore superconducting magnet. The vertical bore is 5·4 cm in diameter, and achieves a maximum field of 82·5 kG. In the absence of a pole piece the maximum value of $H\nabla H = 4{\cdot}66 \times 10^8\,\mathrm{G^2\,cm^{-1}}$. Using a specially designed stepped pole piece (see figure 1) consisting of a Co–V–Fe alloy (49%–2%–49%), we obtained a maximum $H\nabla H$ of approximately $2{\cdot}15 \times 10^9\,\mathrm{G^2\,cm^{-1}}$, sufficient to levitate most organic materials. Moreover, the pole piece was designed to achieve a radially stable region of height 0·2 cm and radius as large as 1·5 cm. The sample was monitored using a 1 m long boroscope and CCD camera. With the aid of a mirror, a side image (perpendicular to the field) was recorded using a standard VCR, which could then be played back frame-by-frame for analysis.

3. Results

To demonstrate the efficacy of the magnetic field for levitation, we first used a polydomain crystal of 12OCB at room temperature. (We measured χ for the polydomain crystal at room temperature using our Faraday susceptometer [7], finding $\chi = 6{\cdot}7 \times 10^{-7}\,\mathrm{erg\,G^{-2}\,g^{-1}}$). Figure 1 shows a schematic diagram of the geometry, where the small circle above the pole piece represents the levitated crystal. The magnet current was rapidly

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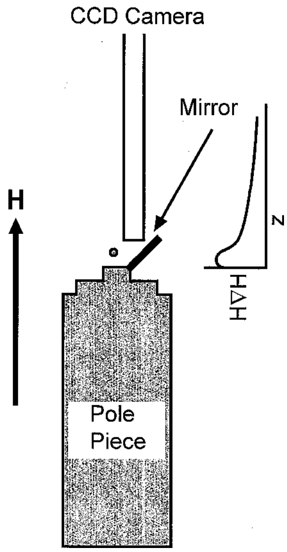

Figure 1. Schematic representation of the magnet—pole piece—imaging system.

ramped up to a current just below that required to levitate the particle. The ramp rate was then slowed to $10\,\mathrm{G\,s^{-1}}$. At one point the crystal jumped off the pole piece and accelerated upward quite rapidly. Unfortunately, the crystal was bound to the surface by a combination of weak van der Waals and charge effects, and did not accelerate smoothly from an initially zero velocity. In consequence the crystal could not be contained in the radially stable region of field. Another attempt was made using a piezoelectric transducer as the base, vibrating at 1 kHz. This was also unsuccessful. Nevertheless, the results show that ML is possible with this class of materials. Figure 2 shows a series of four images, spaced 30 ms apart, of the crystal as it is being levitated. We note that the crystal not only levitates, but reorients in space during this period.

We then attempted to levitate a nematic droplet clinging to a vertically oriented wire. The shape of a liquid droplet on a fibre is an old problem [8–10]. For very small droplets, typically of order 100 μm or less in diameter, the shape is determined by the surface tension and fibre radius. For larger droplet size, however, gravity plays an important role. In earlier calculations gravitational effects were neglected. More recently, however, gravity has been included in theoretical calculations [11], giving results which can be substantially different from the gravity-free case. Nevertheless, experimentalists have long sought a means of examining droplet shape in the absence of gravity. As the magnetic forces in an ML experiment may cancel the gravitational forces, ML provides an appropriate means to study droplet shape on a wire.

For this experiment a varnish-coated copper wire of diameter 0·070 cm was suspended over the centre of the pole piece, at a small angle relative to the magnetic field. The bottom tip of the wire was 0·13 cm above the top of the pole piece. A small quantity of 5CB in the nematic phase—we measured its room temperature susceptibility along the director to be $\chi_{\parallel}=6{\cdot}0\times10^{-7}\,\mathrm{erg\,G^{-2}\,g^{-1}}$—was dripped downward along the wire, collecting in a globule at the bottom of the wire [see figure 3 (*a*)]. From the photograph we estimate that the volume of the liquid crystal was $V\sim3{\cdot}2\times10^{-3}\,\mathrm{cm}^{-3}$. As the field was ramped up near its maximum value, the nematic droplet rose along the wire. Figure 3 (*b*) shows the droplet at the maximum field. The centre of mass of the droplet is stabilized at a height $z_0\sim0{\cdot}30$ cm above the pole piece. We note that $H\nabla H$ is not uniform in space, and therefore the magnetic force varies with both the height z and the radius r, *relative to the magnet axis.* (Recall that the wire is tilted relative to the magnet axis.) For $z<z_0$ the magnitude of the vertical component of $F_{\mathrm{magnetic}}>g$, and the droplet would rise; for $z>z_0$ $F_{\mathrm{magnetic}}<g$ and the droplet would fall. Here g is the gravitational constant $981\,\mathrm{cm\,s^{-2}}$. Thus, the particle equilibrates with its centre of mass at $z=z_0$. From figure 3 (*b*) it is clear that the droplet has become prolate in shape, characteristic of liquid droplets with contact angle $<90°$.

We now examine the forces acting on the droplet. As just noted the sum of the gravitational and magnetic forces per unit mass is not uniform in space, and thus tends to compress the droplet along the z axis. Moreover, at $z=0{\cdot}3$ cm the radial force is outward from the magnet axis, and varies rapidly with z as well as with r. We note, however, that the *magnitude* of these variations is rather small compared to g, and is smaller than g by one to two orders of magnitude over the dimensions of the droplet. It is unlikely, therefore, that the spatial variation of F_{magnetic} plays a measurable role in determining the droplet shape. Supporting this conclusion are two additional observations. First, exploiting the tilt of the wire, we note that the droplet aligns along the axis of the wire rather than along the field axis. Second, owing to the z-dependence of the radially outward magnetic force, the droplet would have had an inverted pear-shape *if the spatially-varying radial magnetic forces had been important.* As the droplet is symmetric, we conclude that magnetic forces simply levitate the droplet, but play little role in determining its shape. Another possible influence on the droplet shape involves elastic forces and surface anchoring. Owing to the volumetric diamagnetic anisotropy $\Delta\chi_{\mathrm{vol}}$ of the liquid crystal, the director aligns parallel to $\mathbf{H}$ throughout the bulk of the droplet, except possibly within a small magnetic coherence length $\xi=(1/H)(K/\Delta\chi_{\mathrm{vol}})^{1/2}$, where K is an

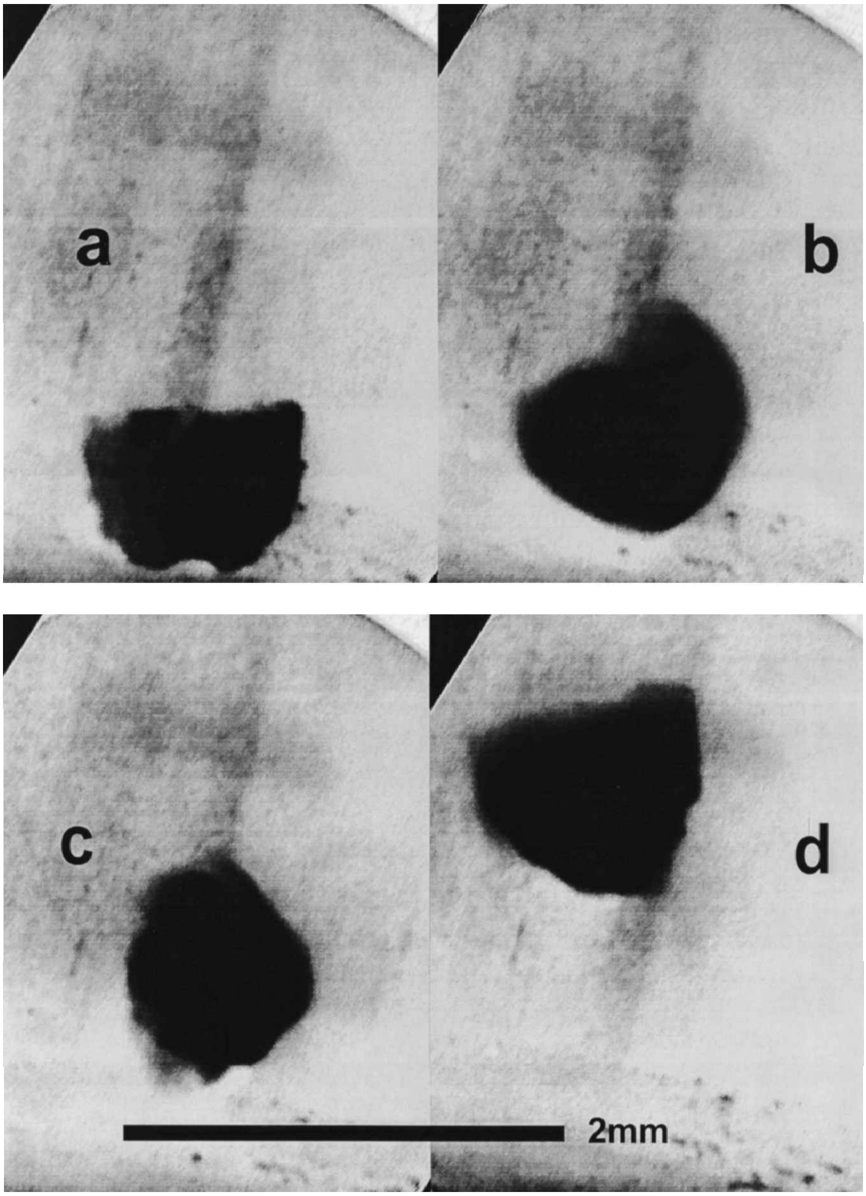

Figure 2. Sequential images of 12OCB polycrystalline sample being levitated. Images are 30 ms spaced.

appropriate elastic constant. If the director were strongly anchored at the air interface, the free energy per unit area $A_{\mathrm{magnetic}}=\frac{1}{2}K(\mathrm{d}\theta/\mathrm{d}x)^2\times\xi$ associated with an orientational distortion θ extending a distance ξ from the surface to the 'bulk interior' would be of order K/ξ. Taking $K\sim1\times10^{-6}$ dyn [12], $\Delta\chi_{\mathrm{vol}}\sim1\times10^{-7}\,\mathrm{erg\,G^{-2}\,cm^{-3}}$ [13] and $H=8\times10^4$ G, we find $\xi<0{\cdot}5\,\mu$m, and therefore $A_{\mathrm{magnetic}}<0{\cdot}1\,\mathrm{erg\,cm^{-2}}$. This is much smaller than typical surface tensions, and is therefore not expected to play a major role.

Thus, we conclude that the droplet shape as it clings to the wire is predominantly determined by the surface tension. Carroll examined this problem theoretically in the absence of gravity [9], attempting to extract the contact angle α (which can be difficult to measure in this geometry) and the droplet length. Defining x_1 as the radius of the wire, x_2 as the maximum radius of the droplet as measured from the centre of the wire, and R_1 and R_2 as the principle radii of curvature at the widest point of the droplet, he obtained an expression for α:

$$\alpha=\cos^{-1}\left[n-\frac{x_1(n^2-1)}{2}\left(\frac{1}{R_1}+\frac{1}{R_2}\right)\right],$$

where $n\equiv x_2/x_1$. From figure 3(*b*) we can easily determine $x_1=0{\cdot}035$ cm, $x_2=0{\cdot}101$ cm, $R_1=0{\cdot}101$ cm, and, by fitting the curvature to a circle, $R_2=0{\cdot}139$ cm. The surface tension, which is typically $\gamma\sim30\,\mathrm{erg\,cm^{-2}}$ and relatively insensitive to phase [14], enters the problem implicitly through α and the empirical quantities x_1 and

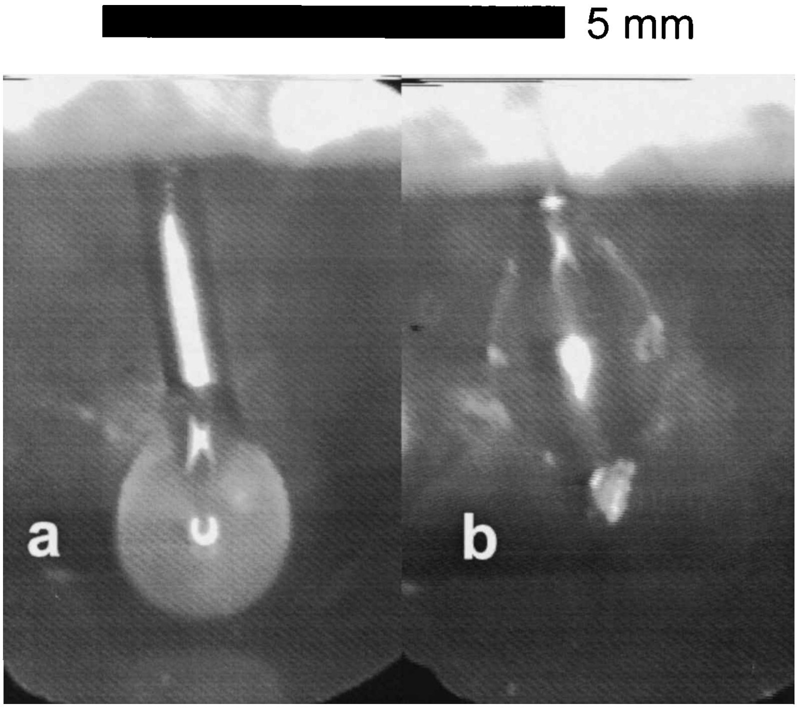

Figure 3. Droplet suspended from wire (*a*) in zero field and (*b*) at maximum field, such that $H\nabla H \sim 2{\cdot}15 \times 10^9\ \mathrm{G}^2\ \mathrm{cm}^{-1}$.

x_2. We therefore find that the contact angle $\alpha = 46°$. This is a particularly difficult figure to determine experimentally for a droplet on a fibre. Additionally, we can extract the pressure difference ΔP across the droplet surface at its widest point, as well as the droplet length. By assuming that $\gamma = 30\ \mathrm{erg\,cm}^{-2}$ and $\Delta P = \gamma(1/R_1 + 1/R_2)$ [9], we find $\Delta P \sim 510\ \mathrm{dyn\,cm}^{-2}$. The droplet length L is given by

$$L = 2[a x_1 F(\varphi,k) + x_2 E(\varphi,k)]$$

where $F(\varphi,k)$ and $E(\varphi,k)$ are elliptic integrals of the first and second kind, $a \equiv (x_2 \cos\alpha - x_1)/(x_2 - x_1 \cos\alpha)$, and $\vartheta \equiv \sin^{-1}[1/k^2(1-(x_1^2/x_2^2))]^{1/2}$, where $k^2 \equiv (x_2^2 - a^2 x_1^2)/x_2^2$. From α, x_1, and x_2, we find that $L \sim 0{\cdot}24$ cm. Within experimental error (± 3 per cent), this value is the same as the length determined directly from figure 3 (*b*). [Note that because of unwanted reflections, the location of the wire's surface in figure 3 (*b*) must be inferred from its known diameter.] Thus, the gravity-free model may be realized by using a large magnetic field gradient to offset the effects of gravity.

ML may provide a variety of new and interesting applications in the field of liquid crystals and complex fluids. The ability nearly to cancel gravity facilitates the investigation of interfacial phenomena and dynamics in the absence of a bounding surface.

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