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We present the first observations of dc electric-field-induced rotational motion of finite particles in liquid crystals. We show that the electrorotation is essentially identical to the well-known Quincke rotation, which in liquid crystals triggers an additional translational motion at higher fields. In the smectic phase the translational motion is confined to the two-dimensional geometry of smectic layers, in contrast to the isotropic and nematic phases, where the particles can move in all three dimensions. We demonstrate that by a proper analysis of the electrorotation, one can determine the in-plane viscosity of smectic liquid crystals. This method needs only a small amount of material, does not require uniform alignment over large areas, and enables probing rheological properties locally.

Electrophoresis, i.e., electrically induced rotational and translational motion of small particles in fluids, is an ancient, but still active science [1]. Most electrophoretic motions are allowed by symmetry (e.g., along the field), however, some motions require symmetry-breaking transitions, and appear only above a threshold electric field. An example of the latter is a dc electric-field-induced steady rotation of solid spherical objects that, in isotropic liquids, was observed first in 1893 by Weiler [2] (Quincke rotation [3]), but was explained only in 1984 by Jones [4]. Another interesting example is an induced translational motion normal to the electric field. This has been observed only for long, slender particles whose charges vary along their contour [5] and was explained in terms of coupling between surface charge and shape modulation [6]. Electrophoretic studies in liquid crystals are scarce [7] and are limited to motions of nanoparticles in lyotropic liquid crystals that do not require symmetry-breaking transitions. It is clear, however, that the techniques based on one-bead microrheology [8] developed recently to monitor the mechanical properties of viscoelastic soft materials [9], might be extremely helpful in analyzing rheological properties of smectic liquid crystal materials, which can be consid-

$$E_r^2 = \alpha \eta [(1+)(1+)]/[\varepsilon (1-\tau/\tau_r)\tau \ ]. \qquad (1)$$

This expression is valid both for spheres and slender cylinders; only the parameters are different. For spheres [15] $\alpha=4/3$, $=2\varepsilon/\varepsilon_r$, $=\sigma_r/2\sigma$, and $\tau =(\varepsilon_r+2\varepsilon)/(\sigma_r+2\sigma)$, whereas for slender cylinders [14] $\alpha=1$, $=\varepsilon/\varepsilon_r$, $=\sigma_r/\sigma$, and $\tau =(\varepsilon_r+\varepsilon)/(\sigma_r+\sigma)$. In these expressions ε, σ (ε_r, σ_r) are the dielectric constant and electrical conductivity of the liquid (solid), respectively, τ is the Maxwell-Wagner interfacial polarization relaxation time, and η is the viscosity.

For both spheres and cylinders, the angular velocity as a function of the applied field can be given as

$$\omega = \frac{1}{\tau}\sqrt{\frac{E^2}{E_r^2}-1}. \qquad (2)$$

In case of our slender cylinder-liquid crystal system, where $\sigma_\sim \gg \sigma_r$ and $\varepsilon_\sim \sim \varepsilon_r$, the expression for the threshold electric field simplifies to

$$E_r^2 = \eta\frac{\sigma_\sim}{\varepsilon_\cdot^2 \varepsilon_\sim \varepsilon_r}, \qquad (3)$$

where the relevant viscosity corresponds to the Miesovitz component η, because the shear plane is perpendicular to the director [10]. From the measured threshold field, additional electrical conductivity and the dielectric constants data one can get the viscosity from Eq. (3). With the parameters of CS2003 at 50 °C listed above, we get $\eta=6$ Pa s, whereas in case of 8CB at 32 °C we obtain only $\eta \sim 1$ Pa s.

Actually, we can determine the viscosity, even without the need for measuring the conductivity and the dielectric constant of the LC, by measuring both E_r and ω, and combining Eqs. (2) and (3), giving

$$\omega(E) = \frac{E_r^2 \varepsilon_r \varepsilon_\sim}{\eta(1+\varepsilon_r/\varepsilon_\sim)}\sqrt{\frac{E^2}{E_r^2}-1}. \qquad (4)$$

For $E \gg E_r$, this further simplifies to $\omega(E)=E_r \varepsilon_r \varepsilon_0 E/\eta(1+\varepsilon_r/\varepsilon_\sim)$. In spite of the ambiguity in determining the angular velocity near the threshold, the electric field dependence of the measured angular frequency can be satisfactorily fitted by Eq. (4) [see Fig. 1(e) for CS2003 at 50 °C and 59 °C], giving $\eta =5.5$ Pa s and $\eta =0.9$ Pa s, at 50 °C and 59 °C, respectively. Electrorotation measurements for 8CB at 32 °C gave $E_r =0.6$ V/μm and $\omega(E E_r)/E \sim 12 \times 10^{-6}$ mV^{-1} s^{-1}, which provide $\eta =1.6$ Pa s. These values are in fairly good agreement with the results obtained using conductivity and dielectric data, and only the threshold field measurement. We note that η was already measured for 8CB, and it was found [16] to be ~ 1.5 Pa s at shear rates corresponding to the highest rates (50 s^{-1}) in our experiments. This agreement clearly indicates that electrorotation of cylindrical inclusions can be used to study the rheology of liquid crystals.

At further increasing fields, the rotating cylinders are set into translational motion at $E_t > E_r$. In the isotropic and nematic phases, the direction of the motion occurs in three dimensions; however, in the smectic phases the axes of the cylinders move strictly along the smectic layers, i.e., the motion is two dimensional. Due to the irregular shape of the edges of the cylinders, the speed of the motion is somewhat irregular. To obtain more reliable results from the field-induced translational motion we studied spherical beads instead of cylinders.

At zero electric fields in the bookshelf smectic layer alignment, the ' , : ⌣ , ⌣ ' are surrounded by two defect "wings" spanning along the layer normal (Fig. 3), similar to defect lines around isotropic droplets in SmA liquid crystals of planar anchoring reported by Blanc and Kleman [17]. The length of the wings is about 30–100 μm in the SmA phases of both 8CB and CS2003, whereas in the SmC^* structure the wings are much shorter (~ 5–10 μm), and sometimes are not even observable.

Although their electrorotation cannot be easily seen (they are too symmetric), careful observations revealed that they also spin around their axes normal to the field, with a thresh-

In the Sm*A* phase of the studied materials, there is a narrow range above E_c.

tric fields E_{th}, which is higher than E_c ($E_c \sim 3.5$ V/μm for CS2003 at $T = 50\,^\circ$C and $E_c \sim 2.5$ V/μm for 8CB at $T = 32\,^\circ$C).

The translational motion takes place along the smectic layers and its direction does not depend on the direction of the gradient of the film thickness up to the wedge angle of 2×10^{-3} rad. FCPM studies show that at zero fields the beads are evenly distributed between the substrates, but when the translational motion is induced, they eventually all end up at either the top or bottom of the film (Figs. 3(d)–3(g)), where they move along the substrates. When the fields are turned off the beads stick to the substrates and do not move back toward the inside of the film.

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