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Rotation of topological defects by trapped micro-rods in the nematic phase of a liquid crystal

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ABSTRACT

The dynamics of rod-shaped micro-particles, trapped within a topological defect, was investigated. It is demonstrated that there is an attractive interaction force between particle and defect, which is of the order of $F \approx 30$ pN, pulling the free micro-rod into the defect core, directing it along the direction of escape. Application of an electric field can induce motion of the trapped rod along the macroscopic path of a circular trajectory, which results in a circular drag motion of the defect's director field. The direction of circular motion can be clockwise or counter-clockwise with equal probability, independent of the sign of the defect. The electric field dependence of trajectory diameter and angular velocity are investigated, and it is found that these lead to a velocity, which is largely independent of electric field and particle-defect rotation direction.

1. Introduction

Over the period of recent years, the introduction of nano- and micro-particles into liquid crystal phases, has become a growing field of research interest [1]. This increasing interest in dispersed systems based on anisotropic liquids is due to the vast possibilities of property manipulation offered by these materials, which can be exploited in novel applications and improved performance. Three principle directions of current efforts may be distinguished:

(i) the addition of nanoparticles, often with an added functionality such as ferroelectricity [2–4], magnetic properties [5–7] or directed conductivity like nanotubes [8–11], to a thermotropic liquid crystal. This is often nematic, but can be also be ferroelectric by itself [12–14], such as the SmC* phase, or discotic [15,16] or even lyotropic [17,18].

(ii) The formation of liquid crystalline order from anisotropic particles in isotropic solvents [19–21]. This behaviour has been demonstrated already about one century ago [22], but has largely been neglected so far, despite of the vast variety of systems available, such as inorganic liquid crystals and clays [19], biologically related nanoparticles, such as the tobacco mosaic virus, TMV, and others [22], DNA [23,24] or cellulose nanocrystals [25]. Also nanotubes and graphene oxide [26–30], as well as other micro-rod and nanowire materials can exhibit lyotropic liquid crystalline ordering.

(iii) The use of self-assembly, spontaneous ordering, and topological defects in liquid crystals to assemble nanoparticles [31–33], for example for the use as photonic materials or metamaterials, is increasingly being investigated.

It is this latter aspect that the present study is loosely related to. It is known that the introduction of particles into a uniformly aligned liquid crystal leads to the formation of defects in the vicinity of those particles [34,35]. Depending on the boundary conditions of the dispersed particle, different types of defects may be observed. There are further strong indications that dispersed particles agglomerate in and around defects of the liquid crystal director field [36–38]. Especially for the nematic phase, these defects have in turn been shown to interact, with defects of equal strength but opposite sign attracting each other and annihilating in a process called the Kibble-Zurek mechanism [39–43]. At last, it has been observed that dispersed particles can be transported through the liquid crystal medium (and also the liquid phase), by application of alternating electric fields. This has been demonstrated in the nematic [44], the ferroelectric smectic C* [45], the chiral nematic [46] and the isotropic phase and is attributed to electrophoresis. In contrast to common liquids, the liquid crystal environment gives rise to a variety of novel particle transport properties. The current state of knowledge has been summarized in an excellent review by Lavrentovich [47]. Particle transport occurs only above a certain electric field threshold, which is dependent on the applied frequency. Several different modes of particle motion can be observed in the field amplitude-frequency, (E,f)-parameter space. For micro-particles of spherical symmetry, several different

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modes of particle transport have been observed: (i) no motion below a frequency dependent threshold voltage. (ii) linear particle displacement in a direction perpendicular to the applied electric field direction. (iii) micro-sphere motion along a circular trajectory in a plane normal to the electric field vector. This is not due to the twist escape structure between two defects of opposite sign, as the circular motion is also observed for uniformly oriented liquid crystals and even for the isotropic phase [46,47]. It is believed to be related to electrophoresis. Finally, (iv) random motion for large applied electric fields, which is due to electro-hydrodynamic flow, and which generally represents the upper limit of investigation shortly before dielectric breakdown.

These types of transport are observed for spherically symmetric particles, while rod-like particles, like they are used in the present investigation, show a much more complex behaviour with additional internal degrees of motion, such as rotations around the long and short axes. In this study, we will combine several of the above outlined aspects, such as particle trapping in defects and particle transport in liquid crystals, in an investigation that describes particle mediated defect transport.

2. Experimental

The investigations were carried out by employing a commercially available, room temperature liquid crystal mixture, ZLI-2806, from Merck, Darmstadt, which was used as provided. The liquid crystal has a phase sequence on cooling of Iso 100 N −20 Cryst. (temperatures in °C), and exhibits a negative dielectric anisotropy $\Delta\varepsilon < 0$. The dispersed silica micro-rods were standard spacer rods as used in sandwich cell or display production (PF-15S, Nippon Electric Glass, kindly provided by Uros Tkalec), with a monodisperse width of 1.5 μm, while the length varied between approximately 5-10 μm, averaging at 8.3 μm. They were dispersed in the liquid crystal at minute amounts, such that the particle density was extremely low. This is of importance, as due to the elastic properties of the liquid crystal, the flow fields created during the motion of individual particles may easily influence the motion of other particles in their vicinity. Due to the small diameter of the rods, it is hard to visualize the director configuration around the rods, but comparison with images by Tkalec et al. [48], it appears that the boundary conditions on the rods are homeotropic and leading to a dipolar defect configuration.

Standard sandwich cells of thickness 10 μm and homeotropic boundary conditions were filled by capillary action, and investigated at room temperature in the nematic phase. All investigations were performed with external electric fields applied. This implies that due to the negative dielectric anisotropy the video recordings and the measurements were done at planar orientation of the liquid crystal, despite the homeotropic substrate boundary conditions. This procedure was necessary in order to induce the umbilic defects in the nematic director field.

Time resolved image acquisition in polarized microscopy (POM) was employed to extract the motion of particles. A polarizing microscope (Leica OPTIPOL) was equipped with a digital camera (uEye Gigabit Ethernet UI-5460-C), which was linked to image capture software. The camera frame rate was 56 images per second, of which every second image was extracted from the movies. The time resolution was thus 0.035 s. The spatial resolution of the camera was 1000 × 720 pixel. Square wave alternating electric fields were applied by a function generator (TTi TG1010) in combination with an in-house built power amplifier to induce micro-rod motion. Subsequent image analysis was carried out with software ImageJ, developed at the National Institutes of Health, Maryland, USA.

3. Experimental results and discussion

For cylinder-like, rod-shaped micro-particles, the following qualitative types of motion can specifically be observed: (a) the rotation in the plane of the substrates around the short cylinder axis, which points along the applied electric field, and thus perpendicular to the substrate plane. One can also observe (b) a rotation around the perpendicular short axis, which lies in the substrate plane, thus perpendicular to the electric field vector. It is not clear if there is (c) also a possible rotation around the cylinder's long axis, (may this point along or perpendicular to the applied field direction), because this would be extremely hard to be resolved by optical microscopy. It should also be pointed out, that the translational modes can be superimposed by the rotational ones. One can thus for example observe instances where a micro-rod rotates around its short axis, while moving on a macroscopic circular or linear trajectory.

While these complex combinations are currently subject to detailed quantitative investigations, we will here discuss a slightly different but nonetheless intriguing scenario, involving cylindrical micro-particles in combination with defects. Fig. 1 schematically depicts the situation as a side view of the employed sandwich cells. The umbilic defect is indicated as a director field, which at the point of singularity escapes into the third dimension, where the director is practically undefined. These defects are generally observed when a nematic liquid crystal with negative dielectric anisotropy is switched from homeotropic to planar orientation when applying an electric field.

Two cases, which are very similar and eventually result in the same configuration, can be observed. In case A) the micro-rod is already oriented perpendicular to the bounding substrates, thus along the core of the defect. The particle is attracted towards the defect core and is eventually trapped (see Movie (1), slowed down by a factor 8 from real time). This is the case presented below. Indeed, the trapping force is quite strong, because the particle will not leave the defect again. This is believed to be due to a minimization of the elastic free energy density, as the micro-rod takes up the role of the director field distortion. Not pictured, but nevertheless observed qualitatively, was also case B) where the micro-rod is initially oriented perpendicular to the defect core, thus parallel to the bounding substrates. As the rod is attracted into the core, it is rotated by 90 degrees, so that it fills up an as large as possible portion of the defect core. The particle thus ends in the same situation as for case A), and in both cases, the micro-rod can then be seen to proceed on a circular trajectory, dragging the whole defect and its director field with it, as shown in Movie (2).

Fig. 2 illustrates by micro-photographs the approach of the micro-rod towards the defect core as outlined for case A). While the defect remains practically stationary within the limits of experimental error, the micro-rod is attracted to it and moves on a linear trajectory and at a constant speed of approximately ~30 μm s^{-1} directly into the core. The whole process, as shown in Fig. 2(A)–(I) takes a time period of about 0.3 s, and is graphically depicted as trajectories in Fig. 3(A). A more detailed analysis, determining the distance between micro-rod particle and defect core as a function of time to fusion shows that the motion is linear, in contrast to the square-root behaviour observed in defect annihilation processes. It is not quite clear why the observed motion is in fact linear, with a constant speed, as this behaviour is normally only observed at large separations, for example between two defects of opposite sign, changing to a square-root behaviour close before annihilation [43]. One reason may be that in this case the nonlinear regime, shortly before the rod merges with the defect core, is too small to be resolved with the employed experimental setup. But possibly the here described experiment is in fact different from defect annihilation experiments. It is worthwhile to point out that the determined particle velocity towards the defect is equivalent to recently determined values in the defect annihilation process between two defects at approximately the same separation [49], which was in the limit of large separation distances. By using the determined velocity $v \approx 30\ \mu m\ s^{-1}$, diameter $d \approx 1.5\ \mu m$ and length $l \approx 8\ \mu m$ of the micro-rod, and a typical nematic viscosity of $\eta \approx 70\ mPa \cdot s$ [50], we estimate the force F between the colloidal micro-rod and the defect to be in the range of $F \approx 30$ pN, assuming an attractive force equal to a Stokes drag force, slightly modified for the cylinder particle geometry. The micro-rod, suspended in the

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