

Cosmology in a cell: Defect annihilation in liquid crystals

Topological defects are configurations of the order parameter which cannot be transformed continuously into a uniform state. They have been observed in various areas of physics, such as alloys, semiconductors, particle physics and cosmology. Due to the unique physical properties of topological defects, they are essential to the understanding of non-equilibrium systems, disordered systems, phase transitions, frustrated media, biological systems, etc. For instance, in the standard hot big bang cosmology model, the symmetry-breaking phase transition automatically leads to the formation of various defects. These defects later form the large-scale structures observed in today's universe, such as cosmic strings, textures, and domain walls. However, in many physical systems, such as cosmology, doing experiments which deal with space and time scales beyond the grasp of human manipulation is almost impossible. Fortunately, liquid crystals (LCs) provide an ideal testbed for studying topological defects. One can find various kinds of defects, including disclinations, dislocations, point defects, global defects, domain walls, and monopoles in LCs. Besides, compared to atomic distances in solid state materials, because of the very small elastic constants of LCs, their defects usually extend over several tens of micrometers. Also, due to the inherent optical birefringence of liquid crystals, the defects can be easily observed through a polarizing optical microscopy (POM).

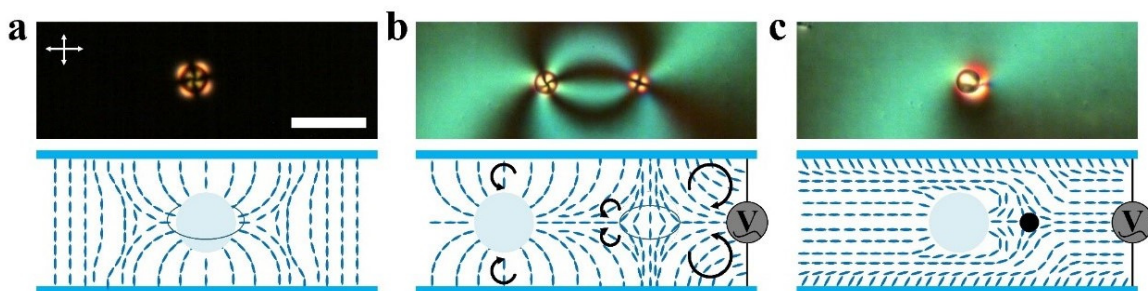


Fig. 1. The POM image (upper) of the particle ($R = 15 \mu\text{m}$) and the negative defect in a cell with homeotropic alignment, as well as the corresponding sketch of the LC director distribution (bottom). (a) the Saturn ring defect encircles the particle without applying electric field. (b) the radial hedgehog defect (particle, $s = +1$) and the corresponding hyperbolic hedgehog defect ($s = -1$) at electric field $E = 0.3 \text{ V}/\mu\text{m}$, $f = 1 \text{ kHz}$ (the black arrows represent the backflows). (c) the hedgehog defect of the particle after the annihilation of (b) at $E = 0.3 \text{ V}/\mu\text{m}$, $f = 1 \text{ kHz}$.

We investigated the annihilation dynamics of topological defects in nematic LCs. In the experiment, a nematic LC with a negative dielectric anisotropy is filled into LC cells with homeotropic surface anchoring (long

molecular axes perpendicular to the glass substrates). At the same time, a small amount of microparticles was added.

After filling, the LC director field far away from the particle is determined by the homeotropic boundary conditions of the substrates. The LC director near the particle is distorted due to the homeotropic surface anchoring on the particle, producing a line defect encircling the particle at the equator, i.e. the Saturn ring defect.

The inner surfaces of the LC cells are coated with transparent indium tin oxide (ITO) electrode layers. An alternating current (AC) electric field which is perpendicular to the cell surfaces is then applied to the LC sample. Due to the negative dielectric anisotropy, the LC molecules realign themselves perpendicularly to the electric field direction, resulting in a symmetry-breaking transition which is accompanied by the formation of a huge amount of umbilic defects. To minimize the free energy, the particle itself acts as a radial hedgehog defect ($s = +1$) which is connected with several hyperbolic hedgehog defects ($s = -1$). Microparticles are thus trapped exclusively in positive defects, while negative defects are particle free. Due to the elastic attraction force, F_a , induced by distorted regions around the particle and the defect, the “positive particle defect” and the negative LC defect slowly move towards each other and eventually annihilate. After the annihilation process, the initial Saturn ring defect encircling the particle will transform into a hyperbolic hedgehog defect located close to the particle in order to satisfy topological constraints.

In the experiment, LC cells with different cell gaps and microparticles with varied diameters were used to investigate the dependence of the annihilation dynamics on these parameters. At the same time, the effects of electric field strength and frequency as well as temperature on the annihilation process were systematically investigated.

In summary, the study shows that the dynamics of the defect annihilation process is related to a complex interplay between elastic attractions, viscous drag forces, backflow effects, director configurations and cell confinement. We hope such a study may eventually provide new insights into the investigation of defects in cosmology.

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