Defects and Design

Nematic liquid crystal boojums with handles on colloidal handlebodies

Q. Liu, B. Senyuk, M. Tasinkevych and I. I. Smalyukh, Proc. Nat. Acad. Sci. (2013) **110**, no. 23, 9231-9236. www.pnas.org/cgi/doi/10.1073/pnas.1301464110

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At sufficiently low temperatures and after sufficiently long equilibration times condensed matter systems will generally reach their lowest energy or *ground* state. But there are usually many possible ground states. In situations involving symmetry breaking from a disordered high temperature phase with a symmetry group G to a low temperature ordered phase with smaller symmetry group H the space of all ground states is the coset space $\mathcal{M} = G/H$ so that there are generally an infinite number of distinct ground states accessible to the system. The actual ground state picked by the system breaks the symmetry relating one ground state to another. In three-dimensional ferromagnets the set of ground states corresponds to the different directions of the net magnetization of the system. Fixing the magnitude of the magnetization leaves all possible directions in space as inequivalent ground states. This is the manifold described by the two-dimensional sphere S^2. For liquid crystals local order is described by an orientation rather than a direction. The inequivalent ground states for a 3D liquid crystal are thus the set of all orientations or lines through the origin which is the two-dimensional projective space RP^2. In both cases the manifold of ground states also has topological structure. RP^2 is particularly rich as it admits point defects, line defects and texture defects. Topological defects correspond to inhomogeneous configurations that cannot relax continuously to uniform configurations. Line defects, for example, correspond to non-contractible loops on the space of ground states $\mathcal{M}$. At some point on any surface bounding such a loop there has to be a point off the ground state - usually taken to be in the high-temperature phase of the system. Varying the surface bounding the loop leads to a continuous line or thread of high-temperature phase trapped in a medium of ordered phase. For liquid crystals these threads (nema in Greek) show up as thin black lines (disclinations) and give rise to the name nematic for the orientationally ordered phase of a liquid crystal. In two-dimensions these defects are point like. As you encircle a disclination defect in 2d the director field of the liquid crystal rotates some integer multiple of π called the strength s of the defect.

The situation is even more interesting if the defects form on curved surfaces of ordered media - the defects in this case are known as boojums. In this case not any set of boojums is consistent with the topology of the surface. The sum of

the strengths of all the boojums on the surface is determined by a topological invariant of the surface known as its Euler characteristic χ. For a closed surface χ is equal to $2 - 2g$, where is the genus or number of handles of the surface.

Liu et al. explore liquid crystalline defects on closed surfaces (i.e those without boundary) by fabricating polymer nanoparticles with the topology of a handlebody of genus g ranging from one to five. These colloidal handlebodies are then inserted into a bulk nematic liquid crystal which orders at the liquid crystal-particle interface. The polymer particles are designed so that the liquid crystals prefer to align along the surface (tangential boundary conditions). Using a combination of holographic last tweezers (HOT), bright-field microscopy, polarizing optical microscopy (POM) and three-photon excitation fluorescence polarizing microscopy (3PEF-PM), the authors control and characterize the director patters that form around these handle body-shaped particles. They are then able to check that the topological constraints are satisfied for several different surfaces.

Topological defects provided mathematical and physical marked points on the colloidal surface. These marked structures are then potential sites for functionalization by attachment of ligands such as alkane-thiols or DNA. Ligands can be then be linked to create bonds between particles. The number of ligands matches the number of defects and determines the effective valence of the colloidal particle. The global arrangement of the defects determines the types of directional bonding exhibited by molecules or clusters of particles. This paves the way for creating a library of building blocks at nano to mess scale that replace quantum mechanical atoms and can self-assemble into colloidal molecules and bulk materials with potentially novel optical, mechanical and thermal response.