Geometric phases in soft materials

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Summary

Geometric phases lead to a nontrivial interference result when an electron's different quantum mechanical paths choices encircle a magnetic coil in an Aharonov-Bohm experiment. They are also responsible for the daily precession of a Foucault pendulum in Paris. A dynamical shape change induces a geometric phase, which, for instance, cats use to rotate when falling and swimmers use to swim forward. A modern application of such geometric phases has led to the notion of topological phases, which are described by a global property of the system. These phases are very different from the classical phases of matter, which are characterized by a local order parameter. A topological phase transition is therefore a fundamentally different process compared to a classical one as in a liquid-gas transition, because the former requires a change of a global topological index of the system. Topological phases can, for example, lead to the presence of traveling electronic modes which are robust against being backscattered by obstacles at the boundary of an insulator. This thesis describes some applications of geometric and topological phases in soft-matter systems.

Chapter 2 focuses on a mechanical metamaterial which is modeled as a network of beads that are connected by means of elastic rods. A designer shape deformation or a spatial variation of the elastic modulus is shown to lead to topologically nonequivalent states in such systems. A boundary between two such nonequivalent systems is predicted to host a domain-bound vibrational mode. This mode amounts to half of the beads vibrating, while the other half are nearly stationary through breaking of a sublattice symmetry of such modes. An application of such a phenomenon is presented as a recipe to enhance this topological mode over all other vibrational modes of the system by damping the vibrations of the second half of the beads. A specific case of such domain-bound modes is extracted as a zeroth Landau-level state by a formulation that maps the dynamical evolution of the vibrational modes of this system to the quantum-mechanical motion of an electron in a magnetic field.

The third and fourth chapters study the light propagation in a liquid-crystal medium. Liquid crystals are complex fluids that combine a unique ability to manipulate light with the reconfigurability of soft materials. They are at the core of modern display technology. Chapter 3 exploits a spatially varying nematic pattern in such systems to find light waveguides that act similar to an optical fiber. An explanation of such waveguiding regimes is through a modifying term to Snell's refraction law due to a spatial inhomogeneity of the geometric Pancharatnam-Berry phase that light acquires by passing through a liquid crystal medium.

Chapter 4 suggests that nematic liquid crystals can also be used as building blocks of topological materials that are key to realize protected unidirectional waveguides, sensors and lasers. Building on recent advances in liquid-crystal technology, it proposes that suitable spatial modulations of the nematic director field are sufficient to assemble topological photonic materials. These ideas pave the way for fully reconfigurable photonic devices based on topologically protected states.

Chapter 5 shifts the focus to convective hydrodynamic systems. Rotating Rayleigh-Bénard experiments as a prototypical model of rotating convective systems are analyzed and the results of an ongoing study on the topological origin of the so-called wall modes in such systems are presented. Simulations of a simplified Swift-Hohenberg model shows wall modes that are robust against severe boundary changes. A linearization of this model around its non-equilibrium steady state in one dimension shows signatures of the topological origin of this protection against backscattering through a non-trivial topological index. A full description of such an out-of-equilibrium system requires a generalization of this topological index for nonlinear models.