Topological matter: A journey from solid state to synthetic quantum systems

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Understanding and harnessing quantum matter is a pivotal goal of many-body physics. Typically, this problem is attacked using the Landau-Ginzburg theory approach, which describes phases in terms of their symmetry content and lack thereof. After the discovery of the quantum Hall effect in 1980, a new, striking element was added into the mix: topological matter.

In these lectures, I shall give an overview of why and how mathematical concepts from topology have been pivotal in understanding paradigmatic phenomena in solid state and atomic systems. Firstly, we will discuss in some detail the archetypical case of the integer quantum Hall effect, starting from experimental evidences and then discussing the direct relation between transport properties and topological invariants within the so called Thouless-Kohmoto-den Nijs-Nightingale treatment. Focusing on this example, I shall try to infer generic features of 'topological' band structures. This will then serve as a guideline for the second lecture, when I will discuss another case sample, the so-called Haldane model, both from a theoretical and an experimental perspective. Finally, in the third lecture, we shall move from topological band structures to the concept of topological order using a dictionary originally developed in chemistry - valence bonds. Again focusing on an example (Kitaev's toric code), I will discuss the weird features of topologically ordered quantum matter, and present an excursus on their potential usefulness as very robust quantum memories.

A list of the topics that shall be covered includes:

First lecture: the magic of the quantum Hall effect.
1) Broad scope introduction: phases of matter in condensed matter systems - aka, why do we need topology?
2) Review of the classical and quantum Hall effect - experimental evidences for quantized transport;
3) TKNN treatment and topological invariants.

Second lecture: imaging topology in atomic physics experiments:
4) Integer quantum Hall effect without magnetic fields: the Haldane model;
5) Experimental signatures of topological band structures in atomic physics experiments.

Third lecture: topological order in interacting quantum systems:
6) Valence bond picture: a chemists' concept for physics applications;
7) The physics of loops and strings, and topologically protected quantum memories.

Prerequisites for attending the lecture: All topics will be presented using minimal (if not negligible) mathematical tools, whilst emphasizing basic physics aspects. As such, a good knowledge of quantum mechanics is sufficient. A background in atomic physics and statistical mechanics is welcome for the second and last lectures, respectively, but not required at all. There is no need at all of quantum field theory and basics of topology, all needed concepts will be introduced over the course of the lectures.