An introduction to topological quantum matter: from gauge theories to topological insulators

February 27, 2017

The scope of this course is to provide an introduction to topological quantum matter, by covering through examples both interacting (in particular, spin liquids) and non-interacting topological matter. The course does not require previous detailed knowledge of quantum field theory. All topics will be covered from a statistical mechanics perspective, with frequent reminders to alternative analytical and numerical methods. While focus will be mostly on the theoretical side, a discussion of few experimentally relevant scenarios in both solid state and atomic physics will be undertaken.

The updated schedule can be found on the statphys calendar at this Link.
Some general references (even well beyond the scope of this course) are the (great!) lecture notes by Motrunich, and the KITP lecture by Lee on spin liquids and magnetism. Finally, a resume of some of the topics discussed here and the Nobel prize in Physics 2016 to Haldane, Kosterlitz and Thouless is available at this link.

I will not follow a specific book or review, but take inspiration from various sources on the different topics. Some useful references are indicated below.

1 Syllabus

1. First part [Lect. 1-2-3]: gauge theories and spin liquids. The main references for this part are Chapters 9 and 17 of Ref. [1], the review by Kogut [4], the original article by Kitaev [3]. For entanglement and topology, nice articles are the review by Regnault [5], and Hermanns [2].

    - brief intro on lattice gauge theories
    - the Ising lattice gauge theory
    - spontaneous symmetry breaking in gauge theories: Elitzur's theorem
    - diagnostics of confinement and deconfinement: Wilson loops and string energy
    - phase diagram of Ising LGTs: non-local order parameters and topological quantum spin liquid
    - dual description of Ising gauge theories
    - quantum dimer models, U(1) spin liquids, and lattice properties
    - dimer models on non-bipartite lattices: Balents-Fisher-Girvin models

- Entanglement and topology: entanglement entropy and entanglement spectra
- braiding statisics, anyons. Examples with the toric code

2. Second part [Lect. 4-5]: non-local order in one-dimensional spin liquids -
   - One-dimensional spin-liquids - hidden order
   - the Haldane chain: string order, hidden symmetries, Kennedy-Tasaki transformation
   - edge states
   - spin-1/2 chains with hidden order, Ising and Kohmoto-Tasaki dualities.

3. Third part [Lect. 6-7-8]: non-interacting topological matter
   - Kitaev model: phase diagram, solution
   - Majorana edge modes
   - integer quantum Hall effect: experimental facts and particles in a magnetic field
   - current quantization and theoretical interpretation
   - towards the Altland-Zirnbauer classification of non-interacting topological matter

2 Other info

Contact. – If you wish to have a chat with me, please contact me first via email - mdalmont@ictp.it - to fix an appointment, so that to avoid you coming to ICTP just to realize that day I'm at SISSA :)

Exam. – There are two ways to take the exam:

1. *Oral exam*: this consists of a small review talk (of approximately 30 minutes) to be given at the end of the course over a certain topic related to topological matter (not necessarily covered over the course). I strongly suggest you take the initiative by proposing something which is of your interest - we can then decide together more specifically which articles should be covered by your review.

2. *hands-on exam*: this consist of reproducing in some detail a paradigmatic result covered over the course with the help of computer simulations (or with analytical methods in specific cases), writing the corresponding (simple) code and briefly presenting it to your peers with a 15 minute talk. In case you feel brave enough, we can even think about a more challenging project, maybe on yet-to-be investigated scenario - which can, obviously carried out within reasonable timescales.

References

[1] E. Fradkin. *Field Theories of Condensed Matter Systems*. Cambridge University Press, 2013.

[2] Maria Hermanns. Entanglement in topological systems. *arXiv preprint arXiv:1702.01525*, 2017.

[3] a. Yu Kitaev. Fault-tolerant quantum computation by anyons. *Ann. Phys. (N. Y).*, 303(1):2–30, 2003.

[4] JB Kogut. An introduction to lattice gauge theory and spin systems. *Rev. Mod. Phys.*, (4), 1979.

[5] N. Regnault. https://arxiv.org/abs/1510.07670. 10 2015.