Topological effects in condensed matter systems

Topology is a branch of mathematics concerned with properties of objects, which are preserved under continuous deformations, including stretching and bending. In past few years a new field of topological materials has emerged in condensed matter physics, based on the wide range of consequences that result from the realization that certain properties of physical systems can be expressed as topological invariants, which are insensitive to local perturbations. The language of topology allows to connect seemingly separate physical phenomena occurring in high-energy and condensed matter physics to each other. Topological quantum numbers are the foundation for the most accurate quantization of observables in condensed matter systems e.g. the ratio of the frequency and dc voltage in the ac Josephson effect and the quantization of the conductance in the quantum Hall effect. The same robustness and accuracy may soon be utilized to revolutionize the field of quantum computing with the help of topological qubits. Moreover, the consideration of the momentum space topology is currently guiding the search of new exotic phases of matter.

We offer a wide range of research projects related to topological insulators, exciton condensates and topological superconductors. One of the most interesting aspects of topological superconductors is that they can support new type of quasiparticles: Majorana zero modes. The interesting property of Majorana zero modes is that they obey exchange statistics different from fermions and bosons. That is, if they are made to interchange positions, the system will transform from one ground state to another, so that these operations correspond to matrix transformations performed on the state of the system. The demonstration of a new type of quantum statistics would be a significant milestone in physics, and it also offers a promise for fault tolerant quantum computation because certain quantum gates can be performed with exponentially small errors. One of the very active research directions in our group is the exploration of the **different platforms for realizing Majorana zero modes**. We are also interested about exploring **exotic transport properties in exciton condensates** and to **utilize topological materials for designing high-temperature superconductors and exciton condensates**.

We look for **candidates with strong analytical or numerical skills (MSc in physics or mathematics)** who find these topics very interesting and want to learn both analytical and numerical methods for studying many particle quantum systems. **No background knowledge related to the research topics is required.** For a successful candidate we offer **a stipend for 4 years (3 500 – 4 500 PLN per month, no taxes)** to work at the International Centre for Interfacing Magnetism and Superconductivity with Topological Matter - MagTop (Scientific Division ON-6, Group of Physics of Majoranas ON 6.5). The successful candidate is expected to **actively take part in international collaboration** in terms of **short-term research stays** and by **participating in conferences** with the funding provided by MagTop. We are currently collaborating with the researchers at **Microsoft Station Q in Santa Barbara, theoretical nanophysics group in Leiden, Quantum Statistical Physics Group in Leipzig** and **Condensed Matter Theory group in Jyväskylä.**

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Further reading relevant for the proposed projects:

1) Press Release: The Nobel Prize in Physics 2016
https://www.nobelprize.org/nobel_prizes/physics/laureates/2016/press.html
(Including the popular science background and scientific background.)

2) M. Z. Hasan and C. L. Kane, *Colloquium: Topological insulators*, Rev. Mod. Phys. 82, 3045 (2010).

3) F. Wilczek, *Majorana returns*, Nature Physics 5, 614 (2009).

4) C. Nayak, S. H. Simon, A. Stern, M. Freedman and S. Das Sarma, *Non-Abelian anyons and topological quantum computation*, Rev. Mod. Phys. 80, 1083 (2008).

5) T. Hyart, B. van Heck, I. C. Fulga, M. Burrello, A. R. Akhmerov, and C. W. J. Beenakker, *Flux-controlled quantum computation with Majorana fermions*, Phys. Rev. B 88, 035121 (2013).

6) *Microsoft Makes Bet Quantum Computing Is Next Breakthrough*, New York Times https://www.nytimes.com/2014/06/24/technology/microsoft-makes-a-bet-on-quantum-computing-research.html

7) *Microsoft Spends Big to Build a Computer Out of Science Fiction*, New York Times https://www.nytimes.com/2016/11/21/technology/microsoft-spends-big-to-build-quantum-computer.html

8) J. P. Eisenstein and A. H. MacDonald, *Bose–Einstein condensation of excitons in bilayer electron systems*, Nature 432, 691 (2004).

9) D. I. Pikulin, P. G. Silvestrov, T. Hyart, *Confinement-deconfinement transition due to spontaneous symmetry breaking in quantum Hall bilayers*, Nature Communications 7, 10462 (2016).

10) T. Hyart, *Viewpoint: A Magnetic-Field-Free Exciton Condensate*, Physics 11, 39 (2018). https://physics.aps.org/articles/v11/39

11) R. Ojajärvi, T. Hyart, M. Silaev, T.T. Heikkilä, *Competition of electron-phonon mediated superconductivity and Stoner magnetism on a flat band*, arXiv:1801.01794.