Kirill Shtengel's Research

The physics of frustration (both classical and quantum), often a signature of strongly correlated systems, has been receiving a lot of attention recently. It is expected that competition between various "conventional" orders favored by different interactions can, at low enough temperatures, lead to new phases of matter with very unconventional properties. One fascinating possibility is so-called fractionalized phases. As the name suggests, the excitations in such phases carry fractions of "normal" particles' charge and spin. In two spatial dimensions, these excitations can also have fractional exchange (or *braiding*) statistics which makes them very attractive candidates for fault-tolerant quantum computation and, in particular, topological quantum computation.

My interests are focused on studying topological order in solids with the special emphasis on Topological Quantum Computation. The two main directions of my research are:

i. Investigating the possibility of topological order in a variety condensed matter systems such as frustrated magnets, bosonic and fermionic extended Hubbard models and related Josephson junction arrays, as well as ultra-cold atomic systems in optical traps. I am focusing specifically on non-Abelian topological order, the conditions under which it may occur and possible methods of its experimental detection.

ii. Studying the feasibility of using non-Abelian topological phases, specifically those expected to exist in Fractional Quantum Hall systems, for fault-tolerant quantum computation. Such an approach, recently dubbed "anyonics" by F. Wilczek, has an important potential advantage over more "conventional" quantum computing schemes: the error correction is automatically built into the correlated electron physics of an underlying solid state system.

Despite the great potential promise of topological quantum computation, many of the basic practical questions, which have been addressed at least partially in the case of more conventional qubit schemes, remain open. They must be resolved in order for this idea to become a reality, and they touch upon fundamental issues in physics. The first question is whether these non-Abelian topological phases actually exist in nature and specifically, in Quantum Hall systems. The second concern is the possibility of creating and manipulating quasiparticles in these systems, and in particular, whether their braiding can be performed in a practical way. And lastly, the state of the anyonic system should be susceptible to certain experimental probes – despite the fact that it cannot be measured easily by the environment. These questions are at the core of my current research efforts.

The broader impacts of this research go well beyond the usual promise associated with quantum computing such as formidable, often exponential speed-up of important computational tasks with implications ranging from cryptography to quantum chemistry. The conceptual idea of topological quantum computation already has had a large impact due to the deep connections it establishes between topology, condensed matter physics and quantum computation. Some of the best experimental groups in the United States and abroad are currently racing to verify the striking predictions stemming from the recent research in this field, including my own.

Below is a short synopsis of my recent work towards these underlined goals.

Starting with my earlier work on topological phases [*C. Nayak and K. Shtengel, "Microscopic models of two-dimensional magnets with fractionalized excitations", Phys. Rev.* **B 64**, 064422 (2001)], I have been interested in both microscopic models with topological order and underlying field-theoretic aspects. In particular, we have established the correspondence between a class of *P,T*-invariant non-Abelian topological phases and gauge theories, specifically, doubled $SU(2)_k$ Chern-Simons TQFTs [*M. Freedman et al., "A class of P,T-invariant topological phases of interacting electrons", Ann. Phys.* **310**, 428 (2004)]. We have shown how the combinatorial "loop" construction of the low-energy Hilbert space can be recast in the language of gauge-invariant Wilson loop operators. Along these lines, we later also conjectured the effective field theory of non-Abelian topological quantum critical points [*M. Freedman, C. Nayak and K. Shtengel, "Line of Critical Points in 2+1 Dimensions: Quantum Critical Loop Gases and Non-Abelian Gauge Theory"*, *Phys. Rev. Lett.* **94**, 147205 (2005)]. We also gained additional insight into the ground state properties (such as ground state correlations) from the "plasma analogy", i.e. by relating the squared norm of the ground state in a (2+1)D system to the partition function of a classical 2D system. This later led us to the proof of gaplessness of excitations at an aforementioned quantum critical point, with the dynamical critical exponent being (at least) 2 [*M. Freedman, C. Nayak and K. Shtengel, "Lieb-Schultz-Mattis theorem for quasi-topological systems"*, cond-mat/0508508]. Curiously, all ground-state correlations between *local* operators remain short-raged! This unusual relation between the equal-time correlations and the spectral gap has been also studied in *K. Shtengel et al., "No sliding in time"*, *J. Phys. A: Math. Gen.* **38**, L589 (2005).

A quasi-realistic microscopic model whose special soluble point corresponds to such a non-Abelian topological quantum critical point has been proposed and studied in *M. Freedman, C. Nayak and K. Shtengel, "Extended Hubbard model with ring exchange: a route to a non-Abelian topological phase"*, *Phys. Rev. Lett.* **94**, 066401 (2005). ("Quasi-realistic" here means that while the particular details of the model can be hardly justified by any experimentally studied system, the types of interactions considered in the model *are* realistic and hence finding or constructing a system in this universality class may be just a matter of time.)

My current focus on this type of microscopic models also involves studying frustrated *fermionic* systems. By contrast to their bosonic counterparts, much less is known about fermionic systems whose quantum dynamics has an inherent sign problem. This is not just a computational difficulty but rather a manifestation of additional quantum frustration associated with the fermionic statistics. In the recent paper, *F. Pollmann, J. Betouras, K. Shtengel and P. Fulde, "Correlated Fermions on a Checkerboard Lattice"*, *Phys. Rev. Lett.* **97**, 170407 (2006), we were able to establish an interesting connection between fermionic and bosonic cases. In particular, we identified a large number of fluctuationless states specific to the fermionic case. We have also shown that for a class of liquid-like states, the fermionic sign problem can be gauged away. The immediate goal is to understand whether these findings carry over to other frustrated fermionic models and whether such models can support topological phases not found in the bosonic systems.

Finally, the issue of stability of topological phases to various kind of fluctuations including external fields as well as Ohmic dissipation has been addressed in *S. Trebst et al., "Breakdown of a topological phase: Quantum phase transition in a loop gas model with tension"*, cond-mat/0609048.

The cornerstone of topological quantum computation is the premise that non-Abelian topological phases exist in nature. The prime candidate for finding non-Abelian statistics seems to be the Fractional Quantum Hall state observed at the $\nu=5/2$ plateau. In the recent paper, *P. Bonderson, A. Kitaev and K. Shtengel, "Detecting Non-Abelian Statistics in the $\nu=5/2$ Fractional Quantum Hall State"*, *Phys. Rev. Lett.* **96**, 016803 (2006), we proposed a "smoking gun" experiment designed to probe such non-Abelian statistics. We later extended this proposal to other non-Abelian Fractional Quantum Hall States including $\nu=12/5$ – potentially a strong candidate for use in a topological quantum computer [*P. Bonderson, K. Shtengel and J. Slingerland, "Probing Non-Abelian Statistics with Quasiparticle Interferometry"*, *Phys. Rev. Lett.* **97**, 016401 (2006)]. The latter paper also addresses an important issue of read-out of a result of an anyonic quantum computation. This issue has been further investigated in another recent paper, *P. Bonderson, K. Shtengel and J. Slingerland, "Decoherence of Anyonic Charge in Interferometry Measurements"*, quant-ph/0608119, where we studied the measurement of a *superposition* of anyonic charges.

The ultimate goal of this direction of my research is to bring the powerful general ideas of Topological Quantum Computation one step closer to reality.