Statement of research interests

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I have a broad interest in physics in general. However, what fascinates me the most is the deep consequences of quantum mechanics. In particular I am fascinated by systems where strong correlations lead to novel phenomena. Fortunately, our universe hosts such systems and I have had the pleasure to work on a prominent and extremely rich such example: the quantum Hall effect (QHE).

I want my research to be driven by interesting phenomena rather than by applying the tools I know well to an ever increasing number of problems that happens to fit. This attitude towards physics is essential to me and it keeps me evolving and learning new tools and new physics.

Below, I will briefly summarize my present research and outline possible directions for my future research.

Past and present research

My research so far has focused on the basic understanding of the (fractional) quantum Hall system. Originating from insights from a numerical project (DMRG applied to the fractional QH system), we have obtained a rather comprehensive analytical understanding of various phases present in the QH system in terms of a solvable limit of the interacting many-body problem. A single Landau level (LL) is a one-dimensional system, and on a torus there is a set of single particle states that naturally map the problem onto a 1D lattice model. We have noted that on the very thin torus this reduces to a one-dimensional classical electrostatic problem and the quantum Hall states are manifested as gapped one-dimensional crystals, Tao-Thouless (TT-) states. The fractionally charged excitations appear as domain walls between degenerate ground states, thus the emergence of such in the (2D) QH liquid is intimately connected to the analogous phenomena in (1D) polyacetylene. The TT-states represent, but are extreme forms of, the observed QH states in the bulk and their qualitative properties (such as quasiparticle charge and degeneracies, quantum numbers, relative size of the gaps, hierarchical structure, phase diagram etc.) remain the same.

For the gapless states (observed at e.g. half-filling in the lowest LL), there is always a phase transition at finite thickness to phases different from the gapped TT-states. Also in this case we have been able to find an analytical solution, which is valid for half-filling on a thin, but finite torus. We have shown that this system can be mapped onto an integrable S=1/2 spin chain (in the gapless XY-phase) and the quasiparticles are identified as dipoles . This provides an explicit microscopic example of how weakly interacting quasiparticles moving in a reduced (zero) magnetic field emerge as the low energy sector of strongly interacting electrons in a strong magnetic field.

The non-abelian QH states also have a simple and illuminating manifestation on the thin torus. In this case, there are several types of inequivalent groundstate configurations and the non-trivial degeneracies (that are crucial for the non-abelian statistics of the quasiparticles) are encoded in the different ways domain walls can be formed between the various groundstates. These liquids have attracted great recent interest as they are candidates as building blocks for topological quantum computers (decoherence-free computational devices), and is one of the directions we focus on right now.

We claim that for all the various states discussed above, the thin torus limit is adiabatically connected to the experimental regime in a similar manner as the free electron gas is connected to the Fermi liquids in e.g. metals (strong analytical as well as numerical support is given in our papers).

During the last year we have exploited the somewhat mysterious connection between the fractional QHE and conformal field theory (CFT), that was pioneered by Moore and Read in the early 1990's. We have been able to construct explicit microscopic candidate wave functions in terms CFT correlators for a large set of states in the lowest Landau level. The wave functions obtained by our approach coincide with those due to Laughlin and Jain, whenever these exist and also yield wave functions describing other fractions. At the newly observed filling fraction, 4/11, numerics indicate that the trial wave function is indeed correct. Moreover, the Haldane-Halperin hierarchy, in which the fractionally charged quasiparticles in the vicinity of a given filling fraction condense to form a new groundstate at the new filling, is manifest in our CFT approach. Thus this provides an explicit connection between the hierarchy and composite fermion formulations of the QHE. We have also established that these wave functions coincide with the exact ones in the solvable limit (thin torus), and thus provide the adiabatic connection from this limit to the experimentally accessible regime at the pertinent fractions.

The solvable limit / CFT synthesis has so far resulted in one paper (Phys. Rev. Lett., in press) and several more are in preparation. We have also published several papers focusing on the solvable limit (in Phys. Rev. Lett., Phys. Rev. B and J. Stat. Mech.). More details can be found in my CV and on my homepage: http://www.physto.se/~ejb/ .

Future directions

In the future I would of course like to broaden my perspectives and I see the vast and expanding area of quantum information (QI) as a very interesting direction to head towards. In particular, I am curious about systems where exotic quasiparticles emerge at low energies and their possible applications to QI. Relevant such phenomena tend to occur in low dimensional systems where effects of interaction and disorder are essential.

Today, there is a lot of very interesting progress, experimental as well as theoretical, in this context. On the experimental side, significant progress is being made in several areas. With the use of optical lattices, environments that were unimaginable only a few years ago can be created. Possibly, these advances can be exploited to reach the QH regime of rotating (Bose-Einstein) condensates. Even though the particles (atoms) are predicted to be thrown out at precisely the frequencies needed to enter this regime, there is a chance that an underlying lattice may resolve these problems. Of course, if this were to be realized we would have a new experimental testing ground at our hands. Perhaps the very exotic non-abelian (parafermion) states, originally proposed as candidates for states observed in higher Landau levels in the 2D electron gas, have their best chance of existence in these systems. And of course there may be a chance for us theorists to propose new states of matter in this context. As a matter of fact, we have come across a set of interesting such states in connection to our CFT project (this is yet unpublished).

As already mentioned, systems supporting non-abelian quasiparticles may arise in different contexts, most notably in the QH system and/or in rotating atomic condensates. It has been suggested that these quasiparticles can be used as qbits, thus providing the essential building blocks of a quantum computer. This suggestion has the very appealing feature that it would be almost unaffected by decoherence, since the topological properties of these states make them insensitive to local perturbations. There is also an interesting connection to the study of entanglement in topologically ordered states that connects the worlds of strongly correlated systems and QI.

There is also a tremendous development when it comes to exotic materials. A few years ago graphene---a single layer of graphite---was experimentally discovered to be a stable material and has since then proven to host a number of interesting phenomena, including a new kind of QHE. Other interesting materials of current interest may support p-wave superconductivity, which in turn is intimately connected with non-abelian QH states.

On the theory side, Kitaev has proposed a class of (toy) models with very interesting properties such as fractional and non-abelian statistics. It would be interesting to see if such phases can be seen in optical lattices, where interactions (at least in some sense) can be tuned by turning a nob, or perhaps in the kind of exotic materials discussed above.

On a more abstract level I am very curious about why certain physical theories work as well as they do. In particular, how come that CFT plays such a prominent role in the theory of the QHE? And what is the precise connection to integrable models? I certainly feel that there are deep insights that awaits discovery regarding the connections between the FQHE, CFT and integrable models (in one-dimension). In my past (and present) research I have come across such connections, and indeed I have speculated that Haldane's conjecture for the existence of (lack of) a gap in integer (half-integer) spin chains is closely related to the (lack of) gaps at (even) odd denominator fractions in the QHE.

Of course I cannot work on all of these interesting topics at once. However, to me, doing theoretical physics should be like taking a random walk in the most interesting areas. I will just try to enter this field, and hope that I stumble on the right places (and that I am educated enough to realize when it happens).