Synthetic physics at the edge

"Observation of chiral edge states with neutral fermions in synthetic Hall ribbons",
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Recommended with a commentary by Thierry Giamarchi, DQMP, University of Geneva.

In condensed matter physics the possibility to investigate physics at the edge of a sample has proven an invaluable source of new physical phenomena. Perhaps one of the earlier realization of such a new physics has been provided by the (classical) Hall effect. Since then our investigations of phenomenon at the edge has scaled up with the discovery of various topological excitations in models such as spin one chains, the various incarnations of quantum Hall effects and of course the recently investigated topological insulators and superconductors, just to quote a few examples. Developing systems in which such class of physics can be created and probed is thus of considerable interest.

In addition to condensed matter realizations, in the last decade or so cold atomic systems have proven that they can be used as remarkable quantum simulators of model systems that are of central interest to the condensed matter community [1]. They have also proven that they can in some situation reach physical parameters that would be difficult to reach with conventional systems. This is in particular the case for the realization of magnetic fields. Cold atoms are neutral, so the application of a real magnetic field does not produce the orbital effects that we have learned to love and which are in particular at the root of the aforementioned Hall effects. The cold atom community has thus developed other methods to realize "fake" magnetic fields that can produce such orbital effects. I will not enter in details on how and I refer the reader to a previous Journal club by Jason Ho on this subject [2] commenting on a pioneering paper by I. Spielman et al.. These magnetic fields have the advantage to only produce orbital effects without being polluted by Zeeman ones and allow easily to put one quantum of flux per plaquette on a lattice, a feat that would requite thousands of Teslas for a normal condensed matter system.

In connection with the physics mentioned above it would thus be interesting to have a ribbon of controlled size in which to study the effect of the finite transverse size of the ribbon in the presence of a magnetic field. Realizations of such systems appeared. In particular the Munich group has realized bosonic ladders made of two coupled bosonic tubes in which the effects of a large magnetic field could be studied [3] and showing interesting physics such as chiral edge states.

An interesting alternative solution to obtain such systems and increase in a controlled way number of legs as well as allowing to study fermionic systems has been provided by the Florence group [4], using the flexibility provided by these "fake" magnetic fields [5]. The idea behind their realization is shown in Fig. 1: They used ^{173} Yb atoms which have an $I = 5/2$ nuclear spin [6, 7]. The interaction between the atoms is essentially independent of the nuclear spin, which makes this system a good realization of an $SU(N)$ Hubbard model, in itself a remarkable feat. Here the idea is to use the nuclear spin index (which can go from $I_z = -5/2$ to $I_z = 5/2$ thus providing up to six independent quantum numbers)

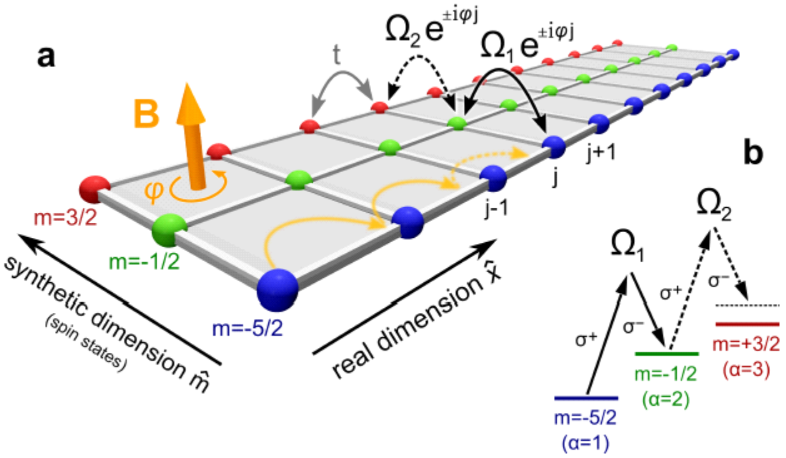

Figure 1: A "fake" ribbon under "magnetic field" with perfectly well defined edges can be realized by using an internal degree of freedom as an extra dimension. a) the realization of a three leg ladder with ^{173} Yb; b) a sketch of the Raman processes that allow the internal degree of freedom to change, mimicking a transverse hopping in a tight binding model. The phase imprinted by the Raman process is similar to what a gauge field corresponding to an external magnetic field would produce for charged particles. (From [4]

as the *chain* index. The internal degree of freedom, thus becomes a "fake" (more professionally called "synthetic") dimension. This allows for a realization of extremely well "laterally" defined ribbons with extremely "sharp" "edges". An example is shown in Fig. 1 where a three legs ribbon using $I_z = -5/2, -1/2, 3/2$ has been used. In order to mimic the transverse hopping and the presence of a "magnetic field", Raman transitions are used between the states with different nuclear spins (see Fig. 1). The phase imprinted in the transition is similar to the one that the vector potential associated to a magnetic field would produce. The system is thus perfectly equivalent to a three leg ladder with a (potentially very large) magnetic field. By choosing the Raman transitions one can modulate at will the number of legs in the ladder and the paper considers both two and three leg ladders.

This remarkable system allows thus to study various aspects of the physics of edge states in systems with magnetic fields using the flexibility and possibility that cold atoms offer. For example measuring the momentum distribution $n_{I_z}(k)$ for a given nuclear spin value gives directly the momentum distribution on each "leg" of the ladder. Both in two and three legs this allows to see the presence of a chiral edge state in a similar fashion to what happened for the bosonic ladder [3].

More interestingly the possibility to monitor the internal degree of freedom allows a "spatial" resolution in a way similar than the one an STM could provide in the condensed matter context, but with the additional possibility to measure position or momentum. For example a system prepared in a given state e.g. $I_z = -5/2$ (thus with particles at on of the "edges"), in which the Raman coupling is switched on suddenly, exhibits oscillations of I_z with time which can be interpreted as the cyclotron orbits (see Fig. 4 of [4]). Both momentum and position can be measured (of course in different measurements !) showing clearly the semicircle "trajectories" of a particle bouncing back on the edge expected for such cyclotron orbits.

Such systems thus opens the door to study phenomena such as Hall and Quantum Hall effects, and other interesting edge phenomena, in cold fermionic systems. Of course the system is not perfect. The main drawbacks at the moment are the following

- So far the physics probed is essentially non-interacting physics. Normally in cold atoms the interaction can be boosted by at least two tricks. The first one is to decrease the kinetic energy by increasing the optical lattice, which make the interactions comparatively stronger. The price to pay is that the temperature effects also become stronger. However as with any fermionic system the temperature is already not that small so it is not clear that the price can be paid without loosing the interesting effects. The second trick is to use Feshbach resonances, but again the presence of several internal degrees of freedom, makes it much more difficult to implement.
- The system has quite peculiar interactions if one want to use the idea of synthetic dimensions. Indeed since all the atoms on the same "rung" are actually on the same physical site in real space, the interaction is totally independent of the "distance" along the rung, while local along the real dimension. Although peculiar and different from a truly local model in two dimensions, this is not per se a drawback since it can also lead to interesting new effects.

Despite these limitations the system offers many interesting possibilities. Exploring synthetic gauge fields in synthetic dimensions might sound a little bit esoteric but will undoubtedly lead to very real physics.

References

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