When holes lose their statistics

The search for exotic quantum spin liquids is one of the challenges of modern condensed matter physics. The term quantum spin "liquid" refers to a state of interacting spins on a lattice that remains a disordered state even at low temperature. Philip Anderson proposed that the parent (insulating) state of the cuprate High-Temperature Superconductors, is in fact of this type, a special liquid made of spin singlet pairs of electrons. In his theory, once the pairs are broken, the liquid exhibits a separation of the spin and the charge degrees of freedom (and superconductivity). Each original electron fractionalizes into two emergent particles, a holon carrying the charge quantum and a spinon carrying the spin quantum. Although the original electron is a fermion, the question of the actual statistics of holons and spinons in such a "deconfinement" scenario remains an open issue.

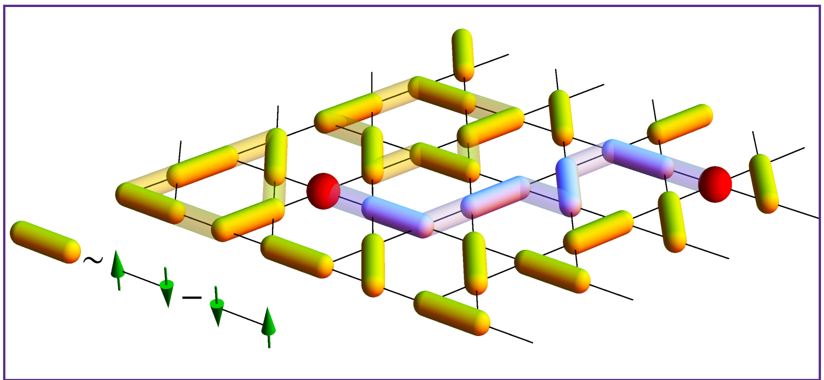

Figure 1: Schematic snapshot of a doped dimer configuration with no particular order on the kagome lattice. Each lattice site is either involved with a neighbouring site in a spin singlet dimer of electrons (the coloured rods), or else occupied by a hole (red spheres). Quantum fluctuations on dimers are represented by resonating loops (yellow transparent and opaque dimers). Holes move along a given path (blue) by switching of the electron dimers from site to site, thus changing the background of dimers.

Anderson's proposal dates from 1987. He suggested that the strange behaviour of cuprate (copper oxide) materials, at the transition between the superconducting and the magnetically ordered insulating phases, could be described by a so called resonating valence bond (RVB) state. In the RVB state, pre-existing spin singlet pairs of electrons become charged superconducting pairs when the insulator is doped with holes by removing electrons.

Just one year later appeared the first effective model to describe magnetically disordered phases in which the magnetic degrees of freedom are disregarded in favour of the more pertinent singlet degrees of freedom whose quantum dynamics are quantum resonating loops of singlet pairs of nearest neighbour electrons dubbed "dimers" (see Fig.1).This is in fact a model of the "Quantum Dimer" type. The description of a magnetic system by a quantum dimer model was performed successfully in Heisenberg antiferromagnets on "frustrated" lattices, such as the kagome lattice (a triangular lattice of triangles), as presented in Fig.1. The existence of Resonating Valence Bond spin singlet liquid phases appears to be confirmed in such quantum dimer models, as well as in certain antiferromagnets. Hence the issue of superconductivity in doped spin liquids becomes a more pressing question.

Doping of (i.e. removing electrons from) a RVB spin liquid is expected to induce a novel type of elementary excitation called a "holon", that behaves as a quasi-particle carrying electric charge e but no spin. Superconductivity may be realized if the holons "proliferate" (condense), but the nature of the superconducting phase is an open question.

At least naively, one could imagine that the resulting superconductor would be "exotic" with a condensation of charge-e holons, instead of the usual charge-2e Cooper pairs. A fundamental issue in this problem is the statistics of these holons; to condense without forming pairs, they must be bosons, otherwise the Pauli exclusion principle for fermions would prevent such a scenario. Interestingly, a "transmutation" of the statistics is possible in such systems: the statistics of holons as elementary excitations appearing in the low-energy limit can be different from the statistics assigned to holes in the original spin 1/2 microscopic model.

We summarise here the results of recent theoretical work on this problem carried out with collaborators at Toulouse, the University of La Plata (Argentina) and the University of Tokyo. We obtained evidence for the existence of a dynamical statistical transmutation in doped quantum dimer models. The dimer quantum dynamics experienced by the holons can transmute their original statistics, e.g. from fermions to bosons. More particularly, we have established a rigorous and general proof establishing that boson holes in a given dimer background are equivalent to fermion holes with other dimer fluctuations. This means that while dealing with fermion holons in the original spin model, holes can be transmuted from fermions to bosons dynamically, thanks to the quantum fluctuations of the singlet background.

This result opens amazing possibilities as for example the detection, via a gauge invariant holon Green's function (involving a string of dimers as illustrated in Fig. 1) similar to that of Quantum Electrodynamics, of rather strong and direct evidence for the existence of an exotic superfluid phase due to condensation of holons carrying a single charge e (a "charge-e superfluid phase"). This is a spectacular example obtained from our theory at intermediate values of the doping, where the system seems to switch from a standard Fermi liquid to a (bosonic) charge-e superfluid phase.

The above kinds of dynamical statistical transmutations have different physical signatures and can be controlled in principle via the microscopic parameters (spin coupling, electron hopping and interactions...). Our results provide motivation for investigating, in a new light, different microscopic models which may give rise to the doped Quantum Dimer Model as an effective model which captures the low energy physics of the original spin systems.

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FURTHER READING

STATISTICAL TRANSMUTATION IN DOPED QUANTUM DIMER MODELS
C. A. Lamas, A. Ralko, D. C. Cabra, D. Poilblanc & P. Pujol,
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HOLE STATISTICS AND SUPERFLUID PHASES IN QUANTUM DIMER MODELS
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