Splintering the electron: A route to high temperature superconductivity?

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In addition to the striking high temperature superconducting state, the cuprate materials exhibit a rich variety of low temperature charge and spin ordered phases. Moreover, the "normal state" at higher temperatures is anything but normal, particularly in the underdoped regime where a strange "pseudo-gap" is observed. Distilling the underlying root cause of the high temperature superconductivity is greatly impeded by this complexity.

Perhaps the only small parameter available to the desperate theorist searching for the underlying mechanism is the temperature itself - the richness of behavior only sets in at temperatures well below electronic energy scales. Consequently, it seems likely that disentangling the secret behind the superconductivity will require an understanding of proximate zero temperature "quantum phases". History also serves as a useful quide here - the metallic phase above T_c in conventional superconductors is a quantum fluid with electron-like low energy quasiparticle excitations, characteristic of the $T = 0$ Fermi liquid phase. Within the much heralded BCS theory of conventional superconductivity, these quasiparticles pair together under the influence of a phonon mediated attraction. Condensation of the resulting charge $2e$ Cooper pairs causes superconductivity. Is the strange behavior of the cuprates outside the superconducting state similarly characteristic of a more exotic $T = 0$ phase, and if so does the high temperature superconductivity emerge naturally from it? A brash theoretical scenario, proposed originally by Phil Anderson [1] and fleshed out in recent years [2,3], identifies a culprit quantum phase within which the electron splinters into pieces. A number of recent experiments offer tantalizing supporting hints.

Many quantum phases can be characterized by an "order parameter", signifying the presence of charge or spin order in the ground state. For example, charge density wave order results when an electron pairs with a *hole*, and condenses into a finite momentum state, in close analogy with BCS theory. Such condensation invariably involves breaking a symmetry, leading to low energy collective excitations. Concomitantly, the *single* electron excitations are oftentimes pushed up above an energy gap. But sometimes quantum phases possess a much more subtle form of order not manifest in a charge or spin order parameter. The fractional quantized Hall phases, which occur in semiconductor heterostructures in the presence of intense magnetic fields, are fluids with neither density wave order nor gapless collective excitations. Moreover, the elementary excitations above the energy gap carry fractional charge - of $e/3$ for the one-third filled Landau level. These phases do possess a hidden "topological" order [4], which can also be understood in terms of a "pairing and condensation" - each electron binds to three vortices, quantized swirls of electric current, and the electron-vortex composite condenses. The condensation of vortex triplets leads directly to electron "fractionalization" into thirds. The topological character of the resultant order is only directly manifest in a gedanken experiment - if the electrons are confined to move on a surface of non-zero genus the ground state is degenerate.

Soon after the discovery of high temperature superconductivity, Phil Anderson suggested that the electron was similarly being "fractionalized" in these materials [1], splintering into separate spin and charge carrying excitations. It is now apparent that such "spin-charge separation" implies a form of topological order quite analogous to the fractional quantized Hall effect [3,4]. When two vortices pair and condense, the Cooper pair is split into two, leading to an exotic bosonic particle - a "chargon" - with the charge of the electron. The electron splinters into the chargon and a "spinon" excitation, which carries the electron's spin and Fermi statistics. The "topological" order again implies ground state degeneracies on surfaces of non zero genus. Ring exchange processes have been suggested as an important ingredient driving spin-charge separation.

Do the undoped cuprate materials possess such a hidden topological order? Their Neel antiferromagnetic order is readily observable in neutron scattering, but experimental signatures for a hidden topological order are subtle. Very broad spectral features in angle resolved photoemmission experiments (ARPES) do suggest that the electron is decaying into constituent pieces. Further support is provided by mid-infrared optical absorption and Raman measurements which exhibit broad spectral features perhaps indicative of spinon excitations. If the signatures of this topological order are so fleeting, why should one care whether or not it is present? The answer is simple - if present in the undoped parent compound, doping leads naturally to high temperature superconductivity.

How so? Superconductivity requires condensation of a charged boson, such as the Cooper pair of BCS theory. Since the electron has Fermi statistics a direct condensation is *not* possible. But with "topological order" the electron splinters, shedding it's Fermi statistics to the spinon, leaving behind a charge e boson which *can* con-