SET based experiments for HTSC materials

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Abstract

The cuprates seem to exhibit statistics, dimensionality and phase transitions in novel ways. The nature of excitations [i.e. quasiparticle or collective], spin-charge separation, stripes [static and dynamics], inhomogeneities, psuedogap, effect of impurity dopings [e.g. Zn, Ni] and any other phenomenon in these materials must be consistently understood. In this note we suggest Single Electron Tunneling Transistor [SET] based experiments to understand the role of charge dynamics in these systems. Assuming that SET operates as an efficient charge detection system we can expect to understand the underlying physics of charge transport and charge fluctuations in these materials for a range of doping. Experiments such as these can be classed in a general sense as mesoscopic and nano characterization of cuprates and related materials.
In a previous work one of us has advanced the conjecture that one should attempt to model the phenomena of antiferromagnetism and superconductivity by using quantum symmetry group. Following this conjecture to model the phenomena of antiferromagnetism and superconductivity by quantum symmetry groups, three toy models were proposed, namely, one based on $\text{SO}_q(3)$ the other two constructed with the $\text{SO}_q(4)$ and $\text{SO}_q(5)$ quantum groups. Possible motivations and rationale for these choices were outlined. In a model to describe quantum liquids in transition from 1d to 2d dimensional crossover using quantum groups was outlined. In the classical group $\text{SO}(7)$ was proposed as a toy model to understand the connections between the competing phases and the phenomenon of pseudogap in High Temperature Superconducting Materials [HTSC]. Then we proposed in an idea to construct a theory based on patching critical points so as to simulate the behavior of systems such as cuprates. To illustrate our idea we considered an example discussed by Frahm et al., . The model deals with antiferromagnetic spin-1 chain doped with spin-1/2 carriers. In the connection between Quantum Groups and 1-dimensional [1-d] structures such as stripes was outlined. The main point of is to emphasize that 1-d structures play an important role in determining the physical behaviour [such as the phases and types of phases these materials are capable of exhibiting] of cuprates and related materials. In order to validate our quantum group conjecture for the cuprates, we have considered the connection between quantum groups and strings.

The cuprates seem to exhibit statistics, dimensionality and phase transitions in novel ways. We summarize the following interesting features that appear to arise in these materials:

- Pseudogap:-We can consider the reduction of the density of states near the Fermi energy as a pseudogap. For example Nakano et al. claim that magnetic susceptibility measurements of the cuprate $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ [LaSCO] in the T-x phase diagram show two crossover lines $T_{\text{max}}(x)$ and $T^*(x)$ [where $T_c<T^*<T_{\text{max}}$]. Thus these
lines $T_{\text{max}}(x)$ and $T^*(x)$ are naturally termed the high and low energy pseudogap respectively. These lines in the T-x diagram are both montonically decreasing with rising hole concentration $x$. Below $T_{\text{max}}$ magnetic susceptibility exhibits a broad peak which in the usual interpretation is taken to arise from the gradual development of the antiferromagnetic spin correlation. The lower crossover line $T^*$ is taken to represent the temperature below which a spin gap opens up in the magnetic excitation spectrum around $q = (\pi, \pi)$.

- Charge-spin separation:-Indications for electron fractionalization from Angle-Resolved Photoemission Spectroscopy [ARPES] have been reported \[11\]. We note that the Fermi liquid is characterized by sharp fermionic quasiparticle excitations and has a discontinuity in the electron momentum distribution function. In contrast the Luttinger liquid is characterized by charge $e$ spin 0 bosons and spin $1/2$ charge 0 and the fermion is a composite of these [i.e. fractionalization]. It is well-known that transport properties are defined via correlation functions. The correlation functions of a Luttinger liquid have a power law decays with exponents that depend on the interaction parameters. Consequently the transport properties of a Luttinger liquid are very different from that of a Fermi liquid. Photoemission experiments on Mott insulating oxides seems to indicate the spinon and holon excitations of a charge Luttinger liquid. However the experimental signatures of Luttinger liquid are not totally convincing. To this end we propose SET based experiments to determine the Luttinger liquid behaviour of the cuprates, see below.

- d-wave symmetry:-Experimental evidence for predominantly d-wave pairing symmetry in both hole- and electron-doped high $T_c$ cuprate superconductors has been reported by C.C. Tsuei and J.R. Kirtley \[12\].
• Stripes:-For recent overview see abstracts of Stripes 2000 conference.

• 1/8 problem:-The recent experimental work of Koike et al. [13] indicates that the dynamical stripe correlations of holes and spins exist in Bi-2212, Y-123 and also La-124 and that they tend to be pinned by a small amount of Zn at $p \approx 1/8^{*}$, leading to 1/8 anomaly.

Keeping the properties of the cuprates and related materials in mind, in this short note we turn our attention to the possibility of Single Electron Tunneling Transistor [SET] based experiments which can probe the charge dynamics in HTSC cuprates. In particular the detection of charge-rich and charge-poor [i.e. stripes] and the important question of detection of fractional charge $q_{f} e$ carried by Luttinger excitation $†$.

• SET coupled to HTSC Josephson junction:-The SET works on Coulomb energy and on the process of tunneling. We can simply define a SET transistor as a small conductor, usually a small metallic island, placed between two bulk external electrodes, that forms two tunnel junctions with these electrodes [14]. The Coulomb charging of the island takes place due to electron tunneling. The current $I$ in this system depends on the electrostatic potential of the island which in turn is controlled by external gate voltage $V_{g}$. The SET transistor operation as a detector entails the measurement of the variations of the voltage $V_{g}$ which is sensitive to the current $I$. It is natural to consider the SET as a quantum detector [14]. The SET transistor is the natural measuring device for the potential quantum logic circuits based on the charge states of

*where $p$ is the hole concentration per Cu

†The Luttinger excitation is fractionalized and the elementary excitation carries the fractional charge $q_{f} e$ instead of the quantum of charge $e$ of the electron
mesoscopic Josephson junctions [14]. It is natural to consider the SET as a quantum
detector if one carefully consider its noise properties [14]. We propose to couple the
SET transistor to HTSC Josephson junction and study the charge dynamics of the
HTSC materials for various levels of doping. The ‘insulating’ layer in the Josephson
junction is chosen for a particular value of doping. For example, in LASCO system it is
known that that superconductivity is suppressed to some extent at hole concentration
per Cu of 1/8. This is considered to be due to existence of stripes. One would expect
measurable change in SET current as one goes from this region towards the purely
AF-phase and purely superconducting. In particular it would be interesting to explore
the transition regions of the T-x phase diagram.

• SET transistor coupled to ‘HTSC material’ SET transistor:- In this set-up we propose
to couple a SET transistor to a ‘HTSC material’ SET transistor. In the simplest case
the ‘metallic’ island in ordinary SET is replaced with ‘HTSC material’ for a value
of doping which is in the region of T-x phase diagram which corresponds to metallic
phase and ‘strange’ metallic [SM] phase. The SM phase is ascribed to coexistence of
superconductivity and stripe phases. In this region the material, if it were perfectly
oriented would be a superconductor in one direction and a strongly-correlated insulator
in the other. Thus one can quantify the SM and metallic phases of HTSC materials in
detail by using charge transport properties measured with SET.

• Single-Cooper pair box:- Tsai et al. [15], have recently demonstrated the time and en-
ergy domain response of an artificially constructed two-level system, which is expected
to form one of the possibilities for the basic bit of quantum computing [Qubit]. This
device which has submicron size allows one to observe quantum coherent oscillations
in a solid state system whose quantum states involved a macroscopic number of quan-
tum particles. As already mentioned it has already been noted [14] that the SET is a natural measuring device for the potential quantum logic circuits based on the charge states of mesoscopic Josephson junctions, such as Single-Cooper pair box of Tsai et al. [15]. Keeping in mind that HTSC materials are doped Mott insulators [unlike the low-temperature superconductors], and consequently their superconductivity depends on the level of doping as is clear from the T-x phase diagram, so that one has under-doped, optimally doped and overdoped regions. It would be interesting to think of an experiment that can give us a detailed look at the effect of changing $T_c$ [as doping is varied] on the charge transport. A possible experimental set-up could consist of SET transistor coupled to a HTSC single-Cooper pair box.

To characterize the transport properties in striped phase in above materials, the experiments must be calibrated against some standard, which clearly shows the one-dimensional transport behaviour and also must be closely related to the cuprate superconductors. One such material is $\text{La}_{1.4-x}\text{Nd}_{0.6}\text{Sr}_x\text{CuO}_4$ ($x=0.1,0.12,0.15$) which is stripe-ordered non-superconducting relative of HTSC cuprates.

In conclusion we have suggested SET based experiments to characterize and understand the underlying physics of charge transport and charge fluctuations in these materials for a range of doping. Experiments such as these can be classed in a general sense as mesoscopic and nano characterization of cuprates and related materials.

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