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Non local interactions in cuprate ladders

1. **Beyond-Hubbard pairing in a cuprate ladder**
   Authors: Hari Padma, Jinu Thomas, Sophia TenHuisen, Wei He, Ziqiang Guan, Jiemin Li, Byungjune Lee, Yu Wang, Seng Huat Lee, Zhiqiang Mao, Hoyoung Jang, Valentina Bisogni, Jonathan Pelliciari, Mark P. M. Dean, Steven Johnston, Matteo Mitrano
   arXiv:2501.10287

2. **Cooper-Pair Localization in the Magnetic Dynamics of a Cuprate Ladder**
   Authors: A. Scheie, P. Laurell, J. Thomas, V. Sharma, A. I. Kolesnikov, G. E. Granroth, Q. Zhang, B. Lake, M. Mihalik Jr., R. I. Bewley, R. S. Eccleston, J. Akimitsu, E. Dagotto, C. D. Batista, G. Alvarez, S. Johnston, and D. A. Tennant
   arXiv:2501.10296

Recommended with a Commentary by Thierry Giamarchi, University of Geneva

There is much interest in understanding the various physical properties and competing phases in high-Tc cuprates. Their two dimensional nature and strong correlations make them particularly resistant to either analytical or numerical approaches.

To address a potentially simpler, but related, problem there has been a strong focus on trying to find simpler structures, in particular one- or quasi- one dimensional, in which similar physics could be addressed in a controlled way. Indeed in one dimension both analytical and numerical techniques (such as in particular the Density Matrix Renormalization Group (DMRG)) provide powerful and controlled techniques to address the physics of such correlated materials. As a result there has been extensive studies in the mid 1990s on such systems – ladders made of coupled 1D legs – using both field theoretical and numerical techniques.

It is out of question to summarize all the various works done on this topic here (for a summary up to 2004, see [1] and references therein) and I will just give the salient points in connection with the two above mentioned papers:

For insulating materials (thus obeying an Heisenberg like Hamiltonian with antiferromagnetic exchange) ladders show a very different ground state depending on the parity of the number of legs (with a similar mechanism than the Haldane mechanism for spin S). Ladders with an even number of legs show a ground state in which the spins are in a singlet ground state and have exponentially decaying spin correlation functions. The excitations in such ladders are thus singlet-triplet excitations. These results have been beautifully confirmed in various experimental compounds.

For doped fermionic ladders with *repulsive* Hubbard like contact interaction quite surprisingly, all spin fluctuations in the ladder are gapped unlike e.g. a single chain Hubbard model which is dominated by antiferromagnetic fluctuations, and the dominant instability is a d-wave superconducting fluctuation (with power-law correlations since one is in 1D). Needless to say obtaining superconductivity (in a controlled theoretical way) out of purely repulsive interactions stirred considerable interest. However finding experimental realizations of such doped systems proved more elusive and this is a point on which I will come back below.

Recently there has been a revival of activity into looking at the excitations of *doped* cuprate ladders and looking at their excitations through various experimental techniques. Following an earlier hint from photoemission [2], the two above mentioned paper looked at the magnetic excitations of doped cuprate ladders using two slightly different compounds (a self doped compound $Sr_{14}Cu_{24}O_{41}$ for paper 1, and a Ca doped compound $Sr_{2.5}Ca_{11.5}Cu_{24}O_{41}$ for paper 2). They also used complementary techniques. Paper 1 looked at the excitations using Resonant Inelastic X-ray scattering (RIXS) while paper 2 used inelastic neutron scattering (INS).

Both paper reached essentially a similar conclusions from the analysis of the excitations and the comparison with 1D calculations (such as DMRG): to explain the observed excitation spectrum (in the framework of a 1D doped ladder) it is necessary to have a much stronger binding of the holes than what would be provided by a Hubbard model with purely contact interactions, and it is necessary to introduce a rather strong nearest neighbor *attraction* of the order of the kinetic energy. Of course the papers themselves do not (and cannot) provide the origin of such an attractive interaction but they seem to differ slightly on their favorite. Paper 1 which is probably quite free of disorder would invoke mechanisms such as electron phonon, or fluctuations, while in paper 2 the binding by localized impurities seem to be an ingredient. In both cases, the comparison between the RIXS data or the INS data and quite controlled DMRG calculations would simply not work without this additional non-local attraction.

This is a remarkable result for various reasons:

- First purely on the methodological level paper 1 showed that RIXS can provide high quality / high resolution (about 35 meV) data which while still higher than the resolutions that can be achieved by INS, definitely put the method on a competitive basis, given its other advantages.

- A similar conclusion was reached by two independent techniques. Even if both look at the magnetic excitations they do not probe exactly the same physics, and therefore the two paper strengthen each other.

- Since such an attractive interaction has been evidenced on the ladder cuprates (see however the caveat below) it is likely that one will have to worry about its presence in all cuprates, or find alternative reasons (other mechanisms, other effects that could be compatible with the observations). Again in the ladder geometry there is no easy way to escape the fact that if one gives oneself an Hamiltonian one can obtain quite reliably the correlation functions.

There is however a slight caveat in the analysis of these papers (not on the data !). The comparison assumes that these systems *when doped* remain ladders. This is a priori not totally obvious. Similar conclusions had initially been reached with similar compounds [3] in the mid 1990s. Undoped such systems are indeed excellent spin ladders since the contact between ladders is a triangular exchange (see for example Fig1 of paper 1 or Fig1 of paper 2). In that case the dominant antiferromagnetic exchange would be frustrated and since in any case the ladders are in singlet state there is practically no interladder magnetic exchange and the compound indeed remains in a quasi-1D configuration where ladders are essentially independent. The situation is quite different when the system is doped since the holes have no difficulty going from one ladder to the next. Thus contrary to the undoped system, in its conducting phase the same system becomes a weakly anisotropic 2D cuprate. The structures are very similar/identical in paper 1 and paper 2 for the cuprate “ladders” studied. Whether this is the same situation here and one has in fact a compound that when doped would still require a two dimensional analysis or whether because of this extra attraction between the holes one remains more in the quasi-1D situation is of course a challenging point but a very exciting one. Measurement of transverse transport, or sensitivity to disorder should provide an interesting answer on that point or at least give additional clues.

It is thus clear that these papers with stir more theoretical activity in the field. On a topic not related to cuprates given the evolution of the RIXS data it would be interesting to see its application to the case of other ladders (even undoped ones) for which magnetic field can be a control parameter. This however means exchanges of the order of 10K or so (to have human magnetic fields) and thus another order of magnitude in the resolution !

References

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