Frustration & Cooperation in strongly correlated exciton condensates

Abstract: Charge and spin degrees of freedom interact intensely in strongly correlated materials. We show that this can lead to either **frustration** (left) or **cooperation** (right) between excitons and magnetic excitations in bilayer systems.

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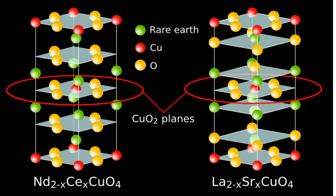
1. Strongly correlated materials

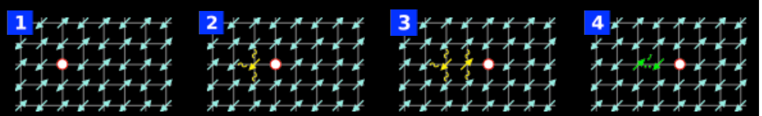
Most electronic properties of materials can be explained using band theory. In the presence of strong electron-electron interactions however this theory is no longer valid. Electrons are localized and only their spin degree of freedom remains. Due to the fermionic character of electrons a proper theory of such strongly correlated materials is unfortunately not known.



Amongst the strongly correlated materials are the well-known high-temperature superconductors: the **cuprates** with their CuO_2 planes.

2. Frustration of moving dopants

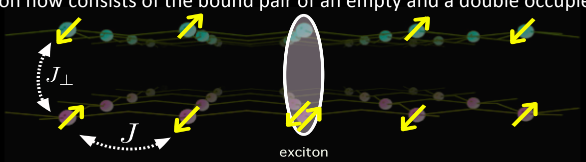
On a square lattice, which is the case in cuprates, the electrons order antiferromagnetically. In a simple classical picture, this prevents the motion of a hole in an antiferromagnet. This effect is called **'frustration'**.



When one includes the quantum flips induced by the Heisenberg interaction the string of upturned spins can be repaired, thus solving the frustration.

3. Bilayer exciton in a strongly correlated material

The bilayer excitons (see right) can also be made in strongly correlated materials. An exciton now consists of the bound pair of an empty and a double occupied site.

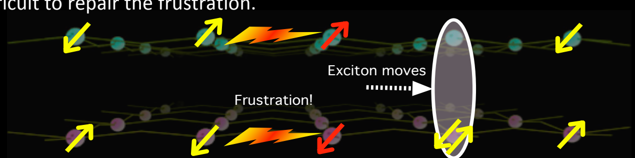


This system is purely bosonic and therefore can be studied in a controlled manner. The **exciton t-J model** is given by the Hamiltonian:

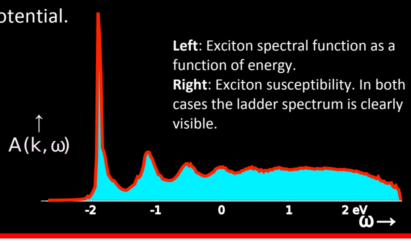
$$\mathcal{H}_{t-J} = J\sum_{\langle ij\rangle,l} \mathbf{s}_{il}\cdot\mathbf{s}_{jl} + J_\perp \sum_i \mathbf{s}_{i1}\cdot\mathbf{s}_{i2} - t\sum_{\langle ij\rangle} |E_j\rangle \left(|0\,0\rangle_i\langle 0\,0|_j + \sum_m |1\,m\rangle_i\langle 1\,m|_j \right) \langle E_i|$$

4. Frustration between excitons and spins

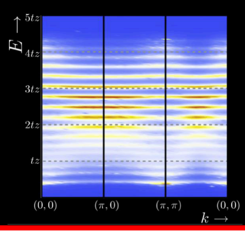
When the exciton hops, this leads to two upturned spins. It is therefore more difficult to repair the frustration.



Indeed, when computing the spectral function of the exciton in a bilayer quantum antiferromagnet it shows clear signals of frustration: the spectrum is independent of momentum and shows a ladder-like structure, reminiscent of a particle trapped in a potential.

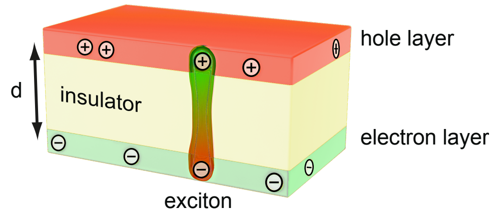


Left: Exciton spectral function as a function of energy.
Right: Exciton susceptibility. In both cases the ladder spectrum is clearly visible.

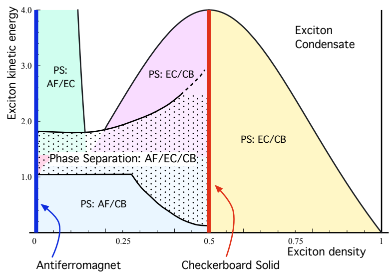


I. Bilayer exciton condensates

An exciton is the bound state of an electron and a hole. Because they attract each other via the strong Coulomb force, they can form bound states and form a superfluid, similar to Cooper pairs. However, an exciton can annihilate. To prevent this one can spatially seperate the hole and the electron, thus creating a **bilayer exciton**. Condensation of bilayer excitons has been achieved in semiconductor quantum wells. We propose to make bilayer excitons in strongly correlated materials.



II. Ground state of a correlated bilayer



Excitons are bosons. The ground state of an ensemble of bosons is either solid or superfluid, separated by a first order phase transition. Additionally, the frustration between excitons and magnetic order (see left side) prevents coexistence of those two. Therefore the phase diagram consists of three phases and a lot of phase separation.

We are interested in the **exciton condensate phase**, which is described by the standard BEC wavefunction:

$$|\Psi\rangle = \prod_i \left(\sqrt{\rho}\,|E\rangle_i + \sqrt{1-\rho}\,|0\,0\rangle_i \right)$$

It is a superposition of the exciton state with interlayer spin singlets.

III. Excitations of a correlated superfluid

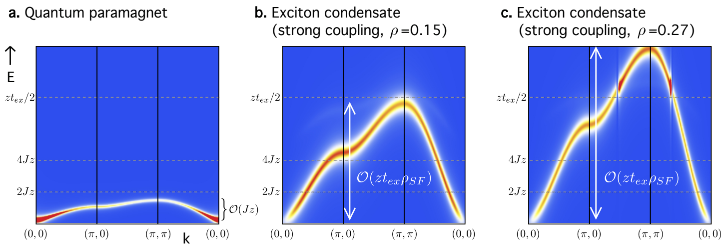
With the exciton t-J model (see Hamiltonian on the left) we can compute the excitations of the superfluid phase using an extended linear spin wave theory. Besides the superfluid phase mode there are gapped propagating magnetic triplet excitations, so-called **'triplons'**.

IV. Cooperation between excitons and spins

Usually the bandwidth of the triplons is set by the superexchange parameter *J*. However, in the presence of condensation the exciton-spin interaction term turns into a triplon hopping term:

$$-t_{ex}\sum_{\langle ij\rangle} e_j^\dagger e_i t_i^\dagger t_j \rightarrow -t_{ex}\sum_{\langle ij\rangle} \langle e_j^\dagger\rangle\langle e_i\rangle t_i^\dagger t_j = -t_{ex}\rho_{\mathrm{SF}}\sum_{\langle ij\rangle} t_i^\dagger t_j$$

Consequently, the bandwidth of the triplon is enhanced thanks to the superfluid, which is visible in the dynamic magnetic susceptibility:



Conclusion: Antiferromagnetic order leads to frustration in the exciton dynamics. On the other hand, exciton condensation leads to an enhanced propagation of magnetic triplet excitations.

References: Rademaker, Wu, Hilgenkamp, Zaanen, EPL 97, 27004 (2012) and Rademaker, Wu, Zaanen, NJP 14, 083040 (2012).

References: Rademaker, van den Brink, Hilgenkamp, Zaanen, arXiv: 1304.3643