Exciton condensation in strongly correlated electron bilayers

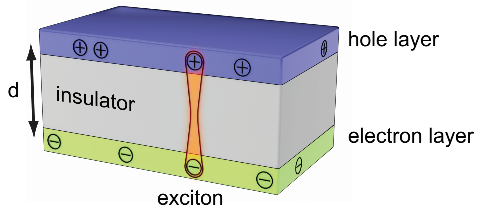
Louk Rademaker[1], Kai Wu[1], Jan Zaanen[1] and Hans Hilgenkamp[1,2]

1: Institute-Lorentz for Theoretical Physics, Leiden University; 2: MESA+ Institute for Nanotechnology, University of Twente

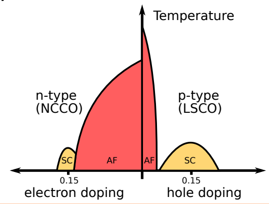
Our idea: combine bilayer excitons and strongly correlated electron systems

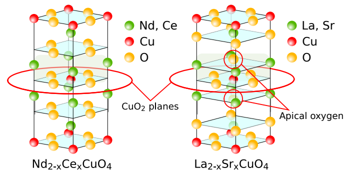
A **bilayer exciton** is an exciton where the hole and electron are spatially separated in two different layers. An insulating layer in between prevents annihilation of the excitons.

Because of their long life-time, bilayer excitons are ideal candidates for realizing a Bose condensate of excitons. [1]



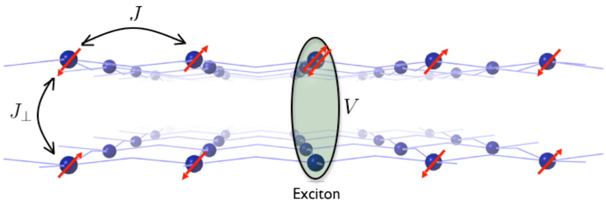
The high-temperature superconducting cuprates are an example of layered **strongly correlated electron systems**.
Because of their quasi-2D nature, strongly correlated electron systems are ideal candidates for bilayer excitons.





What is a bilayer exciton in a strongly correlated background?

In strongly correlated electron systems the electrons are localized, and standard electronic band theory does not apply.



Sideview of a strongly correlated bilayer.
In red the localized electron spin is shown, with antiferromagnetic order.

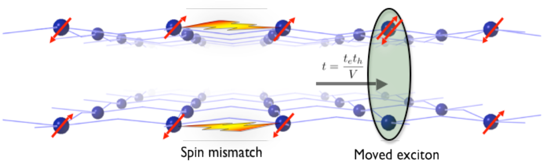
The interaction between the localized electron spins are governed by an antiferromagnetic Heisenberg interaction.

Now a bilayer exciton is the bound state of a doubly occupied and a vacant site.

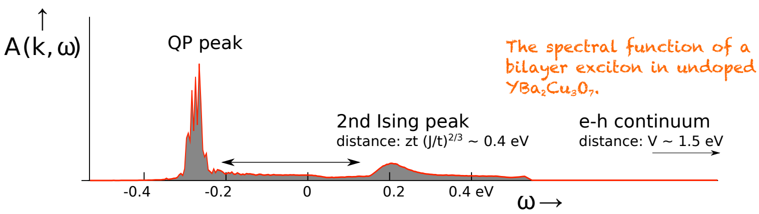
This leads to the following model Hamiltonian:

$$\mathcal{H} = \underbrace{J \sum_{\langle ij \rangle l} \mathbf{S}_{il} \cdot \mathbf{S}_{jl} + J_\perp \sum_i \mathbf{S}_{i1} \cdot \mathbf{S}_{i2}}_{\text{Heisenberg terms}} \underbrace{- t \sum_{\langle ij \rangle} |E_j\rangle \left(|0\,0\rangle_i \langle 0\,0|_j + \sum_m |1\,m\rangle_i \langle 1\,m|_j \right) \langle E_i|}_{\text{Hopping term = exchange of exciton } |E\rangle \text{ with magnetic states } |s\,m\rangle}$$

So what are the **dynamics** of such a bilayer exciton in a strongly correlated system? We know that if the exciton moves, the antiferromagnetic order gets frustrated.



As a result, the exciton is effectively **confined** by the antiferromagnetic spin background. As a signature, the exciton spectral function (measureable with optical absorption) obtains a second **Ising confinement** peak above the first exciton peak. [2]



The spectral function of a bilayer exciton in undoped $YBa_2Cu_3O_7$.

What happens at any finite exciton density?

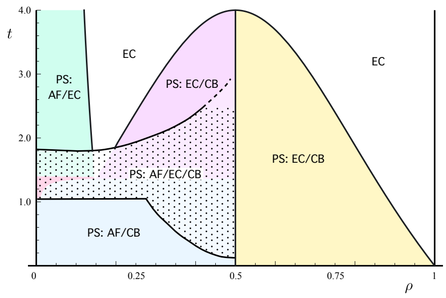
When there is a finite density of excitons, there is strong competition between three different phases:

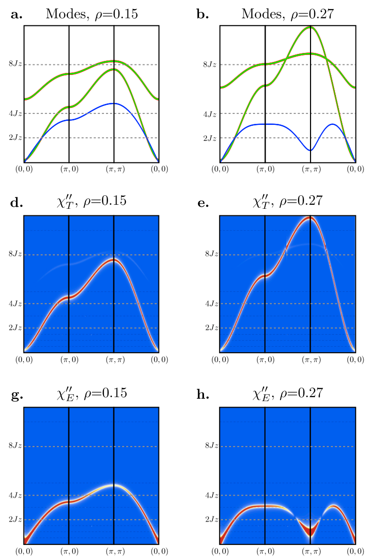
- the **antiferromagnet (AF)** in the absence of excitons;
- the **exciton condensate (EC).** For large exciton hopping, excitons will form a Bose condensate. The wavefunction of the condensate is given by a superposition on each rung of a spin singlet with an exciton:

$$\prod_i (u_i + v_i \hat{E}_i^\dagger)|0\,0\rangle$$

- the **checkerboard phase (CB)** at half-filling, where the strong exciton-exciton repulsion leads to an exciton Wigner crystal.

However, for most parts of the phase diagram the competition leads to **macroscopic phase separation** between these three phases. (See the ground state phase diagram on the right.)





The **collective modes** (see left pictures, for t = 2 eV) of the exciton condensate consist of triplet excitations (middle row) and the exciton superfluid phase mode (bottom row).

The surprise that the triplet modes are characterized by a dispersion with a bandwidth determined by the **superfluid density of the exciton condensate**.

Therefore the superfluid density can be measured in spin fluctuation spectra (neutron scattering). [3]

Universiteit Leiden

References

[1] Eisenstein and MacDonald, *Nature* **432**, 691 (2004)

[2] Rademaker, Wu, Hilgenkamp and Zaanen, *EPL* **97**, 27004 (2012); Rademaker, Wu and Zaanen, *New J. Phys.* **14**, 083040 (2012)

[3] Rademaker, Hilgenkamp and Zaanen, to be published.

Contact & more info

Email: rademaker@lorentz.leidenuniv.nl
Website: loukrademaker.wordpress.com