Exciton condensation in strongly correlated electron bilayers

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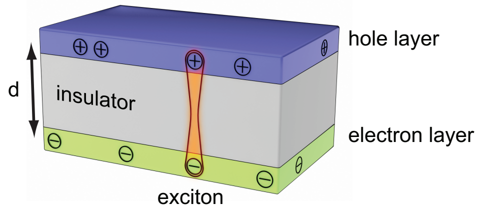
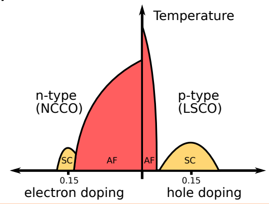
Our idea: combine bilayer excitons and strongly correlated electron systems

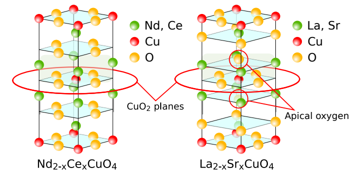
A **bilayer exciton** is an exciton where the hole and electron are spatially separated in two different layers. An insulating layer in between prevents annihilation of the excitons.

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



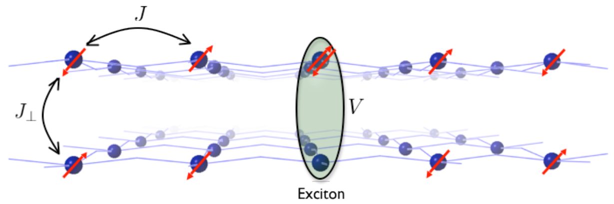
The high-temperature superconducting cuprates are an example of layered **strongly correlated electron systems**.
Because of their quasi-2D nature, strongly correlated electron systems are ideal candidates for bilayer excitons.





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.

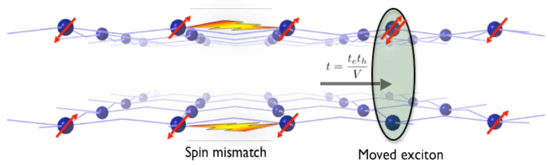
The interaction between the localized electron spins are governed by an antiferromagnetic Heisenberg interaction.
Now a bilayer exciton is the bound state of a doubly occupied and a vacant site.
This leads to the following model Hamiltonian:

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

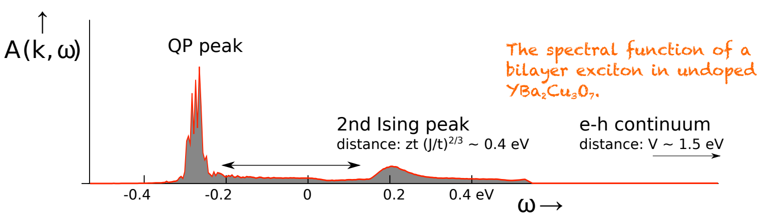
Heisenberg terms

Hopping term = exchange of exciton |E> with magnetic states | s m >

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.



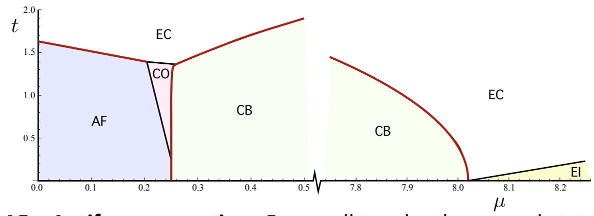
As a result, the exciton is effectively **confined** by the antiferromagnetic spin background. As a signature, the exciton spectral function (measureable with optical absorption) obtains a second **Ising confinement** peak above the first exciton peak. [2]



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

Ground state of a system with nonzero exciton density

We can introduce a finite density of excitons in the ground state. Now bilayer excitons have a repulsive dipole interaction. We can thus compute the **mean field phase diagram** as a function of the exciton chemical potential μ and the exciton hopping t:

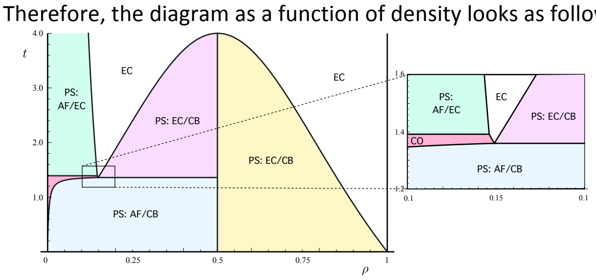


AF = Antiferromagnetism. For small t and μ the ground state is still the Néel state without any excitons.
EC = Exciton condensate. For large exciton hopping, excitons will form a Bose condensate. The wavefunction of the condensate is given by a superposition on each rung of a spin singlet with an exciton:

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

Usually, an exciton condensate is detectable via its enhanced interlayer tunneling. However, because of the singlet ground state the tunneling of opposite spin species cancels each other. Consequently, the 'singlet exciton condensate' has no tunneling matrix element and is therefore a 'dark' exciton condensate.
CB = Checkerboard phase. The excitons form a Wigner crystal structure due to the strong exciton-exciton repulsion.
EI = Excitonic insulator. Boring phase with only excitons.
CO = Coexistence phase of AF and CB.

The red lines in the above phase diagram are first order transitions. Therefore, the diagram as a function of density looks as follows:



In most parts of the phase diagram we find **phase separation** as is customary at a 1st order phase transition. [3]

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References

[1] Eisenstein and MacDonald, Nature **432**, 691 (2004)
[2] Rademaker, Wu, Hilgenkamp and Zaanen, *EPL* **97** 27004 (2012); Rademaker, Wu and Zaanen, arXiv:1202.3616 (to appear in New J. Phys.)
[3] Rademaker, Hilgenkamp and Zaanen, to be published.

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