Excitonic condensation in double-layer graphene

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Outline

Introduction: excitonic condensation

Double-layer graphene in zero magnetic field.

Double-layer graphene in quantum Hall regime.

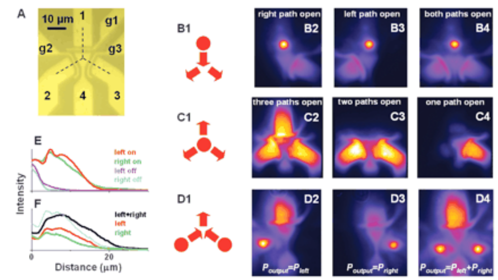
Conclusions

Candidates for excitonic condensation

Yu.E. Lozovik and V.I. Yudson, JETP Lett. 22 (1975)

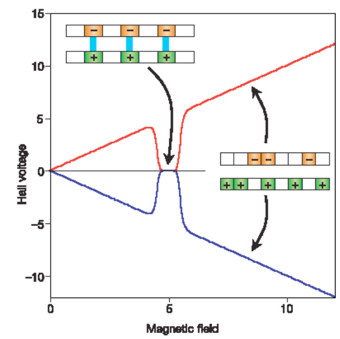
Optically created electron-hole pairs:
A posteriori detection of the condensate via PL.

D. Snoke group, L.V. Butov group (Nature 2002, Science 2004, Science 2008).

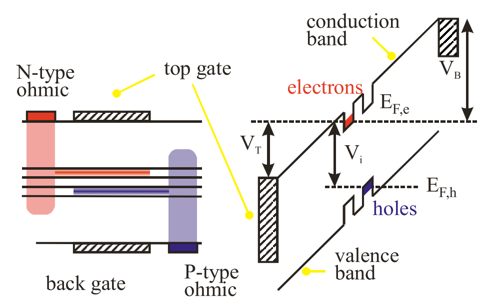


Electron-electron or hole-hole bilayers in magnetic field:
Limited condensate phase space: $\nu_{Total} = 1$

Jim Eistenstein's group, M. Shayegan's group (Nature 2004, Science 2004).



"Equilibrium" electron-hole bilayers:
Need: small d, high mobility, and low temperature.
Problems: Non-nesting bands, different mobilities



M. Lilly et al. App. Phys. Lett. 2007; A.F. Croxall et al. J. Phys. App. 2008

Electron-hole double-layer graphene

Advantages:
Nearly perfect electron-hole band nesting.
Nearly identical mobilities on the electron and hole sides.

In quantum Hall regime, non-uniform states are predicted by mean-field theory and by exact diagonalization.

C.-H. Zhang, YJ PRB 75, 245414 (2007); D. Sheng et al., PRL 100, 116802 (2008)

Same sample can explore e-e and e-h system coherence properties.

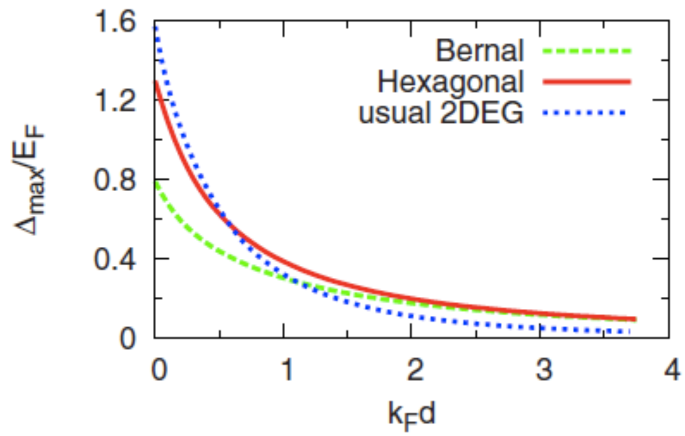
Properties of $\nu_e + \nu_e = 1$ and $\nu_e + \nu_h = 1$ can be compared.

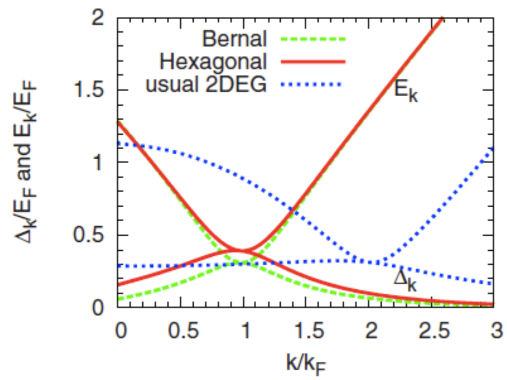
Non-uniform excitonic condensation in quantum Hall regime.

Littlewood and Zhu, Physica Scripta T68, 56 (1996)

B=0: balanced electron-hole graphene

BCS+HF : Linear dispersion + Coulomb interaction *a la* Littlewood





Excitonic condensation is strong when $k_F d \lesssim 1$
Maximum excitonic gap is $\Delta \sim 0.4 E_F$
Mean-field critical temperature is $T_{MF} = 0.2 E_F$

C.-H. Zhang and YJ, PRB 77, 233405 (2008).
H. Min, R. Bistritzer, J.-J. Su, and A.H. MacDonald, PRB 78, 121401(R) (2008).
Yu.E. Lozovik and A.A. Sokolik, JETP Lett. 87, 55 (2007); J. Phys. 129, 012003 (2008).
M.Yu. Kharitonov and K.B. Efetov, PRB 78, 241401 (R) (2008).

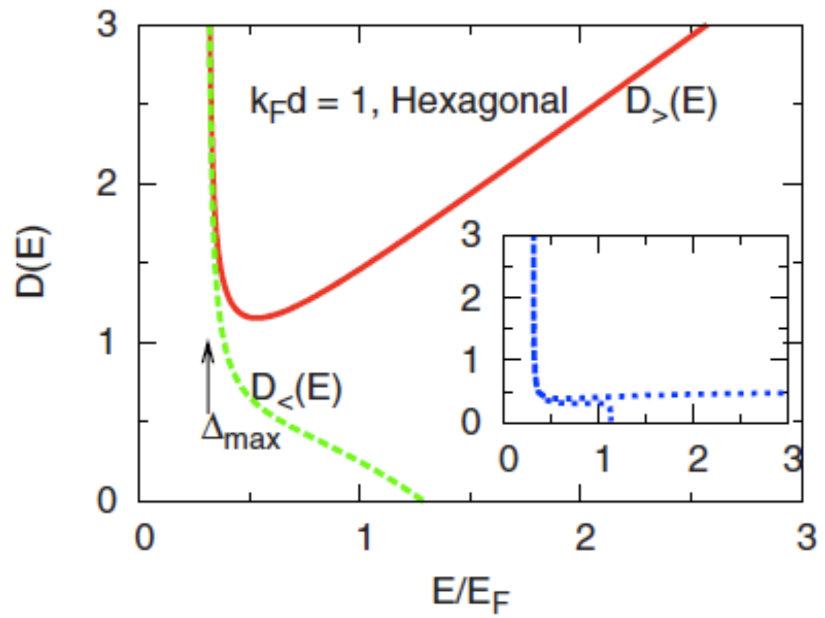
B=0: balanced electron-hole graphene

Linear dispersion + Chiral carrier modified Coulomb interaction.

No “dilute” BEC limit.
H. Dahal et al. PRB 74, 233405 (2006)

Superfluid stiffness and exciton mass both scale as Fermi energy.

Dipolar repulsion between excitons: yet no crystallization.



Does magnetic field lead to non-uniform states in the BCS limit?

C.-H. Zhang and YJ, PRB 77, 233405 (2008).
Yu.E. Lozovik and A.A. Sokolik, JETP Lett. 87, 55 (2007); J. Phys. 129, 012003 (2008).

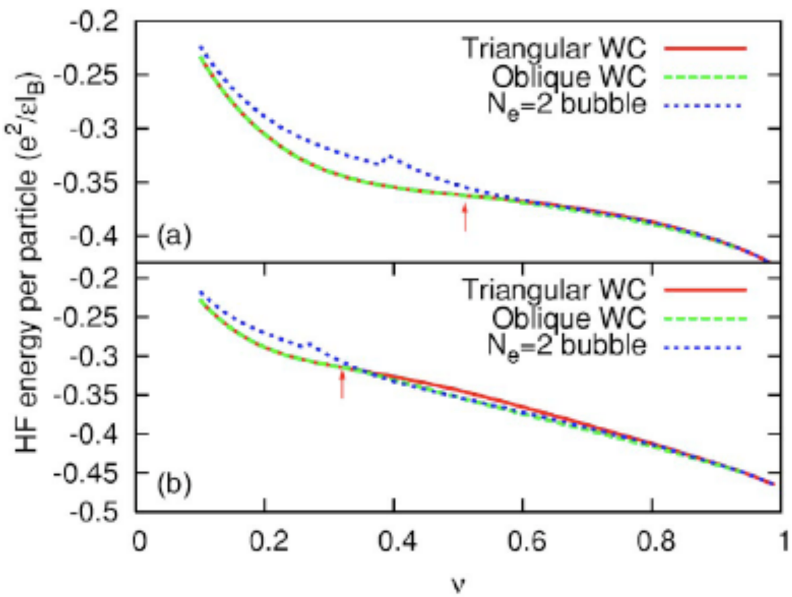
Graphene in Quantum Hall regime

Mean-field analysis predicts anisotropic Wigner crystal states.

Lowest Landau level has triangular Wigner crystal at small filling.

Higher Landau levels have bubble and anisotropic Wigner crystal states.

n=1



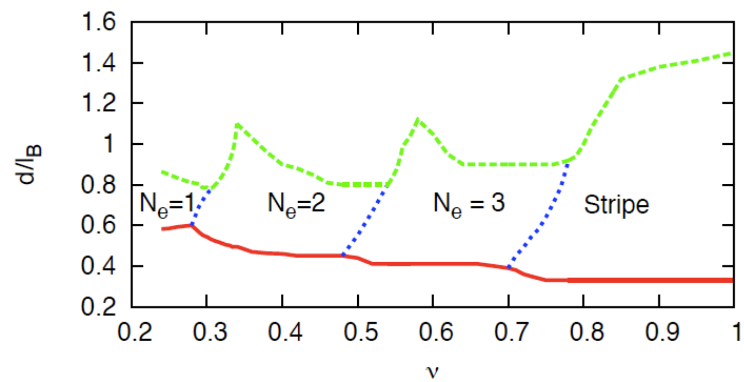
What will happen when two such graphene sheets are closeby?

C.-H. Zhang and YJ, PRB 75, 245414 (2007); PRB 77, 205426 (2008)
D. Sheng et al. PRL 100, 116802 (2008).
H. Fertig article in *Perspectives in Quantum Hall Effects* (1997) Eds. S. Das Sarma and A. Pinczuk

Balanced electron-hole graphene: B!=0

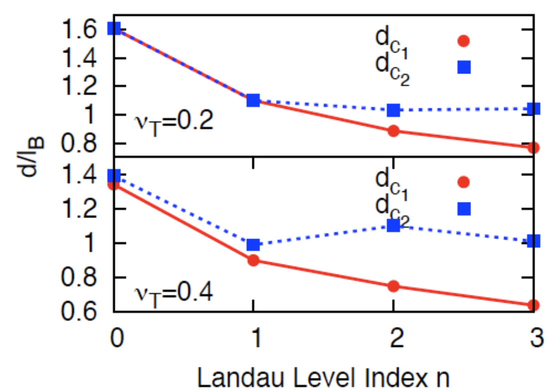
Calculate the density matrix $\rho_{ee}(\mathbf{Q}), \rho_{hh}(\mathbf{Q}), \rho_{eh}(\mathbf{Q})$ in $(d/l_B, \nu_e)$ plane.

n=3



A uniform condensate for small *d*.

Uncorrelated layers with electron and hole Wigner crystals at large *d*.



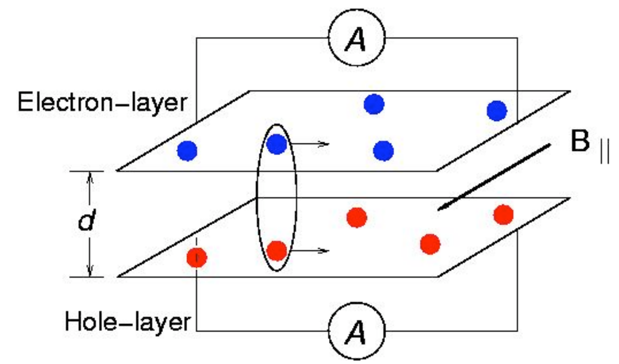
There is a crystalline condensate when $d_{c_1} \leq d \leq d_{c_2}$

Crystalline condensate region *increases* with Landau level index n.

How to detect the excitonic condensate?

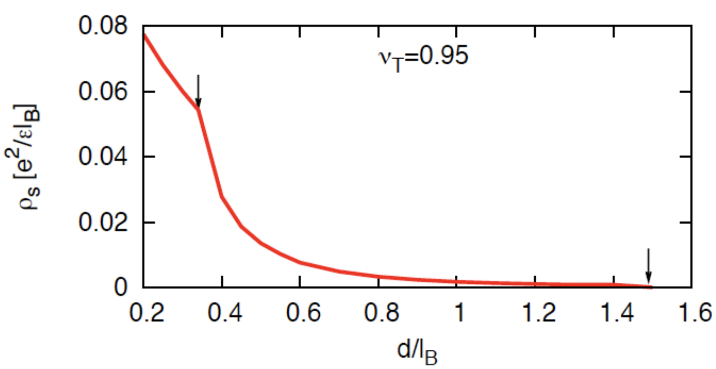
Independently contact the two layers and use an AC magnetic field.

Excitonic condensate phase couples to *difference* of gauge potentials.



Condensate phase stiffness:

$$J_d = 2e^2 \rho_s d B_{||} / \hbar^2$$



A.V. Balatsky et al. PRL 93, 266801 (2004).
YJ, A.V. Balatsky, M.P. Lilly, PRB (2005)

Conclusions

Double-layer graphene is an ideal candidate to explore uniform and non-uniform excitonic condensates.

When B=0, we predict a uniform excitonic condensate and in the quantum Hall regime, we predict a non-uniform excitonic condensate as the ground state at intermediate values of *d*.

Detection: Superfluid response to B field, interlayer drag, PL...

Future work: screening, disorder, tight-binding model, two sheets of bilayer graphene...

Thank You!

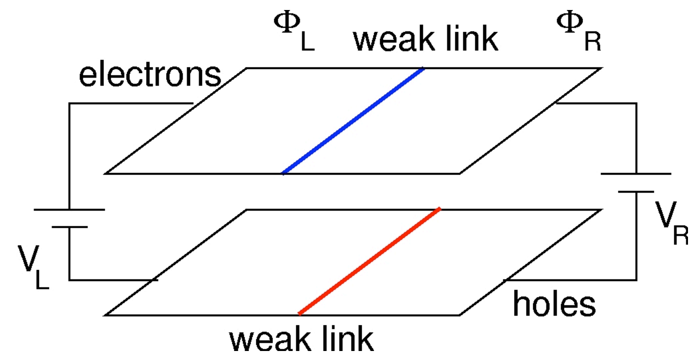
Condensate: a tunable Josephson junction

How does phase difference across a junction evolve with voltage?

Dipolar phases on two sides evolve according to respective voltages.

In-plane Josephson effect!

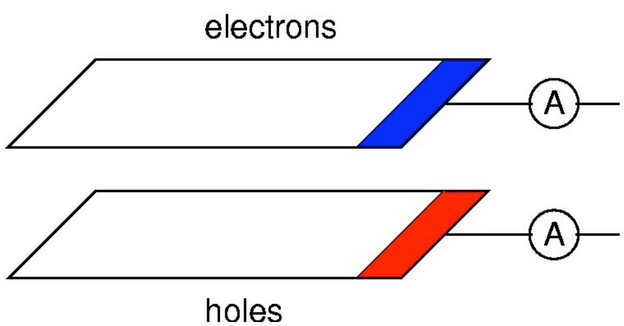
$$\Phi_d(t) = \Phi_d(0) + \int_0^t dt' [V_L(t') - V_R(t')]$$



Critical current is proportional to the product of electron and hole tunneling amplitudes.

How to measure superfluid sound velocity?

Measure correlations between current fluctuations!



Normal Phase:

$$\langle T\delta J_e(\mathbf{r},t)\delta J_h(0,0)\rangle = 0$$

Condensate Phase:

$$\langle \delta J_e \delta J_h\rangle(\omega) = -\frac{2\pi e^2\rho_d}{v_c}|\omega|\theta(v_c\Lambda - |\omega|)$$

Prediction: *Power spectrum of current noise measures the sound-mode velocity.*