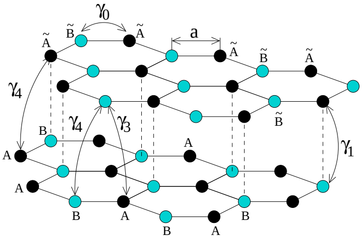
Inter-Landau level magnetoexcitons in bilayer graphene

Exotic Quantum Phases Group - group seminar

2012-10-03

1. Introduction

Tight binding model of graphene



$$\hat{H}_\xi = \xi \begin{pmatrix} \frac{u-\Delta'}{2} & v_3\pi & -v_4\pi^\dagger & v\pi^\dagger \\ v_3\pi^\dagger & -\frac{u+\Delta'}{2} & v\pi & -v_4\pi \\ -v_4\pi & v\pi^\dagger & -\frac{u-\Delta'}{2} & \xi\gamma_1 \\ v\pi & -v_4\pi^\dagger & \xi\gamma_1 & \frac{u+\Delta'}{2} \end{pmatrix} - \Delta_Z\hat{\sigma}_z,$$

where $\pi = p_x + ip_y$ és $\mathbf{p} = -i\hbar\nabla - e\mathbf{A}$, $\xi = 1$ refers to K

$$E_{n\xi} = \mathrm{sgn}(n)\hbar\omega_c\sqrt{|n|(|n|-1)} - \xi\frac{u\hbar\omega_c}{2\gamma_1}$$

E. McCann and V. I. Fal'ko, PRL 96, 086805 (2006)

Magnetoexcitons (mean-field theory)

Magnetoexcitons are created by the operator:

$$\hat{\Psi}^{\dagger}_{NN'}(\mathbf{Q}) = \sqrt{\frac{2\pi\ell_B^2}{A}} \sum_p e^{ipQ_y\ell_B^2} \hat{a}^{\dagger}_{Np} \hat{a}_{N'p-Q_x}$$

Possible quantum numbers:

- spin, pseudospin: S_z, P_z, S, P
- angular momentum quantum number: $l_z = |n| - |n'|$, only at the $q \to 0$

$$\begin{aligned} H^{(\tilde{N}\tilde{N}')}_{(NN')}(\mathbf{Q}) &= \langle 0|\Psi_{\tilde{N}\tilde{N}'}(\mathbf{Q})\hat{V}\Psi^{\dagger}_{NN'}(\mathbf{Q})|0\rangle - \delta_{N\tilde{N}}\delta_{N'\tilde{N}'}\langle 0|\hat{V}|0\rangle \\ &= \delta_{N\tilde{N}}\delta_{N'\tilde{N}'}\left(E_{n\alpha\xi\sigma} - E_{n'\alpha'\xi'\sigma'} + \Delta(n,n')\right) + E^{(\tilde{N}\tilde{N}')}_{(NN')}(\mathbf{Q}) + R^{(\tilde{N}\tilde{N}')}_{(NN')}(\mathbf{Q}) \end{aligned}$$

Exchange self-energy:

$$\begin{aligned} \Delta(N,N') &= \sum_{M \text{ filled}} (X_{N'M} - X_{MN}) \\ X_{N'N} &= \int \frac{d\mathbf{q}}{(2\pi)^2} I^{N'N}_{N'N}(\mathbf{p}) \end{aligned}$$

C. Kallin and B. I. Halperin, PRB 30, 5655 (1984); Iyengar et al. PRB 75, 125430 (2007).

Direct dynamical interaction:

$$E^{(\tilde{N}\tilde{N}')}_{(NN')}(\mathbf{Q}) = -\int \frac{d\mathbf{q}}{(2\pi)^2} e^{i\hat{\mathbf{z}}\cdot(\mathbf{q}\times\mathbf{Q})} I^{N\tilde{N}}_{N'\tilde{N}'}(\mathbf{q})$$

Exchange interaction:

$$R^{(\tilde{N}\tilde{N}')}_{(NN')}(\mathbf{Q}) = \frac{1}{2\pi\ell_B^2}\mathfrak{Re} I^{NN'}_{\tilde{N}\tilde{N}'}(\mathbf{Q})$$

Identities:

$$(-1)^{N+N'+\tilde{N}\tilde{N}'} E^{(\tilde{N}\tilde{N}')}_{(NN')}(\mathbf{Q}) = E^{(NN')}_{(\tilde{N}\tilde{N}')}(\mathbf{Q}) = E^{(\tilde{N}'\tilde{N})}_{(N'N)}(\mathbf{Q})$$

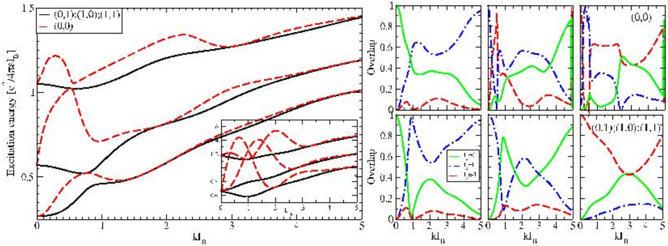
$$R^{(\tilde{N}\tilde{N}')}_{(NN')}(\mathbf{Q}) = R^{(NN')}_{(\tilde{N}\tilde{N}')}(\mathbf{Q}) = (-1)^{N+N'+\tilde{N}\tilde{N}'} R^{(\tilde{N}'\tilde{N})}_{(N'N)}(\mathbf{Q})$$

$$\Delta(n,n') + X_{n'0} + X_{n'1} - X_{n,0} - X_{n,1} = \Delta(-n',-n)$$

$$\begin{aligned}
I^{N_2N_2'}_{N_1N_1'}(\mathbf{p}) &= \frac{2\pi e^2}{\epsilon p}[A^{(n_2')}_{\xi_2'}A^{(n_1)}_{\xi_1}A^{(n_1')}_{\xi_1'}A^{(n_2)}_{\xi_2}F^*_{|N_2||N_2'|}(\mathbf{p})F_{|N_1||N_1'|}(\mathbf{p}) \\
&+ B^{(n_2')}_{\xi_2'}B^{(n_1)}_{\xi_1}B^{(n_1')}_{\xi_1'}B^{(n_2)}_{\xi_2}F^*_{|N_2|-2,|N_2'|-2,}(\mathbf{p})F_{|N_1|-2,|N_1'|-2}(\mathbf{p})] \\
&+ \frac{2\pi e^2}{\epsilon p}e^{-pd}[A^{(n_2')}_{\xi_2'}B^{(n_1)}_{\xi_1}B^{(n_1')}_{\xi_1'}A^{(n_2)}_{\xi_2}F^*_{|N_2||N_2'|}(\mathbf{p})F_{|N_1|-2,|N_1'|-2}(\mathbf{p}) \\
&+ B^{(n_2')}_{\xi_2'}A^{(n_1)}_{\xi_1}A^{(n_1')}_{\xi_1'}B^{(n_2)}_{\xi_2}F^*_{|N_2|-2,|N_2'|-2,}(\mathbf{p})F_{|N_1||N_1'|}(\mathbf{p})]
\end{aligned}$$

Integer quantum Hall states

- for fixed N and N' 16 possible modes
- $l_z = 0, \pm 1$ are examined, with 7 transitions for fixed l_z subspace
- Only $S_z = P_z = 0$ are obversable in either Raman or optical absoption experiments
- mixing removes level crossings, changes the spectra qualitatively



Yu. E. Lozovik and A. A. Sokolik, arXiv:1111.1176 (2011)

Quantum Hall ferromagnetic states

- Integer filling factors including $\pm 3, \pm 2, \pm 1, 0$
- Minimization of interaction energy results in gapped states breaking S or P rotation symmetry or both
- New basis in P subspace required:

$$\hat{a}_{nS\sigma p} = \cos\frac{\theta}{2}\hat{a}_{n,\xi=1,\sigma p} + \sin\frac{\theta}{2}e^{i\phi}\hat{a}_{n,\xi=-1,\sigma p}$$
$$\hat{a}_{nA\sigma p} = \sin\frac{\theta}{2}\hat{a}_{n,\xi=1,\sigma p} - \cos\frac{\theta}{2}e^{i\phi}\hat{a}_{n,\xi=-1,\sigma p}$$

- At $\nu = -1, 3$ partial or full orbital coherence develops (Y. Barlas et al, PRL 104 096802 (2010))
- Magnetoexciton method applies to $\nu = -3, \pm 2, -1, 0$

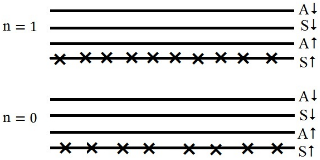
$\nu = \pm 2, 0$

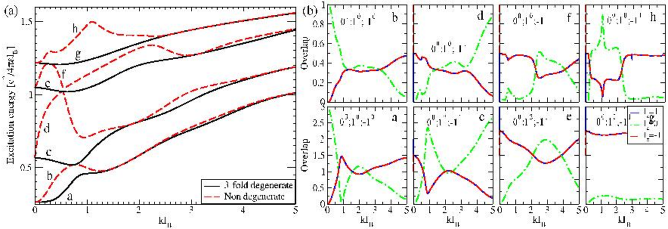
Copperspondng identities (for $\nu = -2$):

$$E^{(2,1)}_{(2,1)} = E^{(1,-2)}_{(1,-2)}$$

$$R^{(2,1)}_{(2,1)} = R^{(1,-2)}_{(1,-2)} = -R^{(1,-2)}_{(2,1)} = -R^{(2,1)}_{(1,-2)}$$

$$\Delta(2,1) + X_{1,0} + X_{1,1} - X_{2,0} - X_{2,1} = \Delta(1,-2)$$



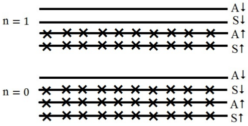


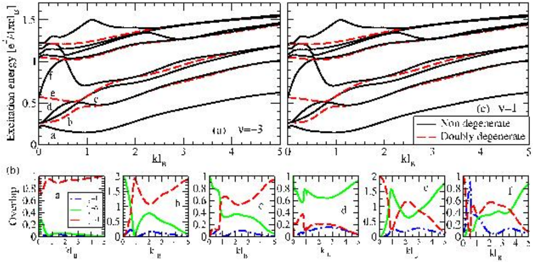
$\nu = -3, 1$

$\nu = -3$


n = 1
n = 0
A↓
S↓
A↑
S↑
A↓
S↓
A↑
S↑

$\nu = 1$


n = 1
n = 0
A↓
S↓
A↑
S↑
A↓
S↓
A↑
S↑


Excitation energy
(a) ν=-3
(c) ν=1
Non degenerate
Doubly degenerate
(b)
Overlap

Conclusions, further aims

- Identified observable transitions of bilayer graphene with integer filling factor
- Mixing of transitions of different Landau levels is strong
- Mixing removes level crossings and smoothens dispersion relations
- Examining the effect of screening instead of the currently used bare Coulomb potential
- Inclusion of further transitions with l_z other than $0, \pm 1$

Thank you for your attention!