Ferromagnetism in the Low Concentration Limit in Conducting Polymers with Pentagon Cell

Zsolt Gulacsi,
University of Debrecen, Department of Theoretical Physics, Debrecen, Hungary.

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University of Debrecen

Location of Debrecen

Main Building

Motivations:

- Conducting polymers are a fascinating class of materials with a strikingly wide range of applications, e.g. in nanoelectronics, nanooptics and medicine.
- The majority of these system have pentagon cell.
- Several of these structures have almost unknown properties. Good quality result for pentagon chain cases are present in the high concentration limit.
- Organic conducting systems have high inter-electronic Coulomb repulsion ($\sim 10eV$), hence poor approximations are misleading.
- The majority of known chains are non-integrable, their good quality description techniques are relatively rare, their understanding is far to be complete.

Short Outline:

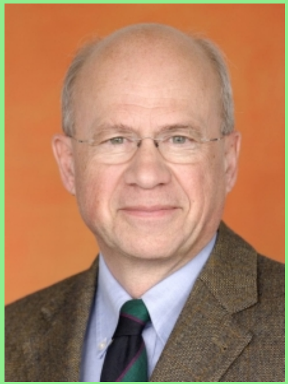
- Introduction (5 %)
- The method used (5 %)
- The steps of the method (40 %)
- Hole doped pentagon chain structures (40 %)
- The mechanism leading to ferromagnetism (5 %)
- Summary and conclusions (5 %)

Collected number of slide pages: 30

Main collaborations on the subject

International collaborations:

A. Kampf



D. Vollhardt

M. Gulacsi

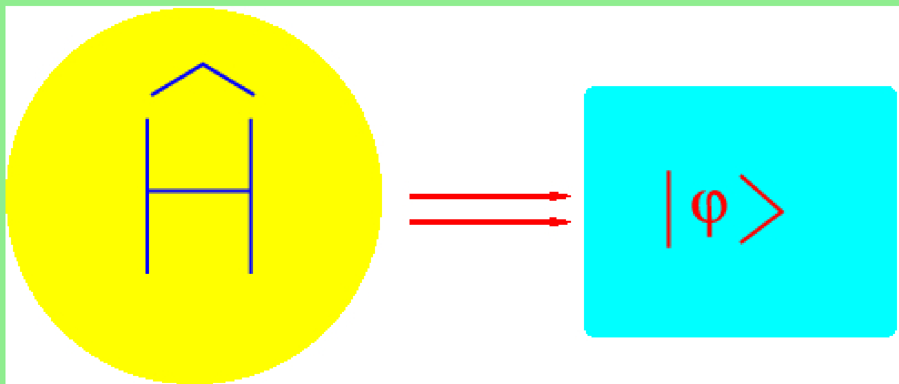
Local people:

Gy. Kovács

E. Kovács

P. Gurin

I. THE METHOD USED, AND STEPS OF THE METHOD



Positive semidefinite operators ($\hat{O}$)

One considers $\langle\Phi|\Phi\rangle = 1$, *the Hilbert space is* $\mathcal{H}$.

By Definition: $\langle\Phi|\hat{O}|\Phi\rangle \geq 0$, $\forall|\Phi\rangle \in \mathcal{H}$

If $|\Phi\rangle$ **is an eigenstate of** $\hat{O}$, **e.g.** $\hat{O}|\Phi\rangle = p|\Phi\rangle$, **it results**

$$\langle\Phi|\hat{O}|\Phi\rangle = p\langle\Phi|\Phi\rangle = p \geq 0$$

Consequently:

The minimum possible eigenvalue of $\hat{O}$ **is zero !**

$\widehat{H}$ as positive semidefinite operator

$\widehat{H}$ for a physical system has always a lover bound E_g of the spectrum

$\widehat{H}|\Psi\rangle = E|\Psi\rangle$, $\quad \forall E, \quad E \geq E_g$,
where $\widehat{H}|\Psi_g\rangle = E_g|\Psi_g\rangle$ **defines** $|\Psi_g\rangle, E_g$

Consequently:

$\forall \widehat{H}$, $\widehat{H}' = \widehat{H} - E_g = \widehat{O} =$ **Positive Semidefinite Operator**

e.g. $\quad \forall \widehat{H}$, $\quad \widehat{H} = \widehat{O} + C$, $\quad$ **where** $C = E_g$. **Hence:**

a) The ground state is obtained from: $\widehat{O}|\Psi_g\rangle = 0$.

b) The procedure is independent on D or integrability.

The steps of the method

Step 1: Decomposition in positive semidefinite operators

Meaning: Rewrite the starting $\hat{H}$ as $\hat{H} \equiv \hat{O} + C$, (2)

<u>This job is done by:</u>

- Introduction at each lattice site of block operators $\hat{A}_{\mathbf{i},\sigma}$ as linear or non-linear combination of fermionic operators acting on the sites of a given finite block, than creating positive semidefinite forms as for example $\hat{A}^{\dagger}_{\mathbf{i},\sigma}\hat{A}_{\mathbf{i},\sigma}$.

- Introduction of other possible positive semidefinite operators as $\hat{P}_{\mathbf{i}} = \hat{n}_{\mathbf{i},\sigma}\hat{n}_{\mathbf{i},-\sigma} - (\hat{n}_{\mathbf{i},\sigma} + \hat{n}_{\mathbf{i},-\sigma}) + 1$,

- Matching the value of $\hat{H}$ parameters and positive semidefinite operator coefficients such to obtain Eq.(2). This leads to the *<u>Matching Equations</u>*.

The steps of the method

Step 2: Construction of the ground states

Meaning: Construct the most general $|\Psi_g\rangle$ such to have $\hat{O}|\Psi_g\rangle = 0$. The corresponding $E_g = C$.

Precondition: The Matching Equations must be solved first

Matching Conditions: Nonlinear complex algebraic system of coupled equations (2D often $\sim 40-50$).

- **One obtains explicitly: $\hat{A}_{\mathrm{i}}$ from transformed $\hat{H}$, $\hat{H}(\mathcal{D})$.**
- **Only after this step the $|\Psi_g\rangle$ construction can begin.**

The steps of the method

Step 3: The proof of the uniqueness

Meaning: To prove that the deduced $|\Psi_g\rangle$ is unique.

The procedure is based on the study of the kernel:

Let $\hat{O} = \hat{H} - E_g$. Then, $ker(\hat{O}) := \{|\phi\rangle, \hat{O}|\phi\rangle = 0\}$.

One must prove that $|\Psi_g\rangle$ spans $ker(\hat{O})$.

The technique has two steps:

a) One proves that $|\Psi_g\rangle \in ker(\hat{O})$

b) One proves that all $|\Phi\rangle \in ker(\hat{O})$ can be written in terms of $|\Psi_g\rangle$

c) When degeneracy is present $|\Psi_g\rangle \to |\Psi_g(m)\rangle, \forall m$

The steps of the method

Step 4: The study of physical properties

Meaning: The deduced $|\Psi_g\rangle$, has usually a quite complicated structure, and the physical properties, a priori, are not visible. They must be deduced !

This is done by calculating different expectation values

Remarc: If $(|\Psi_g(N)\rangle, E_g(N))$ is deduced, also the low lying spectrum can be tested. E.g., the charge gap ($\triangle$):

$$\delta\mu = \mu_+ - \mu_- = [(E_g(N+1) - E_g(N)) - (E_g(N) - E_g(N-1))],$$

Where: $\delta\mu = 0, (\delta\mu \neq 0)$, **means** $\triangle = 0$, ($\triangle \neq 0$).

The steps of the method

References:

Reporting papers:

Z.G, D.Vollhardt, Phys. Rev. Lett. 91,186401(2003),

Z.G,A.Kampf,D.Vollhardt, Phys.Rev.Lett.99,026404(2007),

Z.G, A.K, D.V, Phys. Rev. Lett. 105,266403(2010),

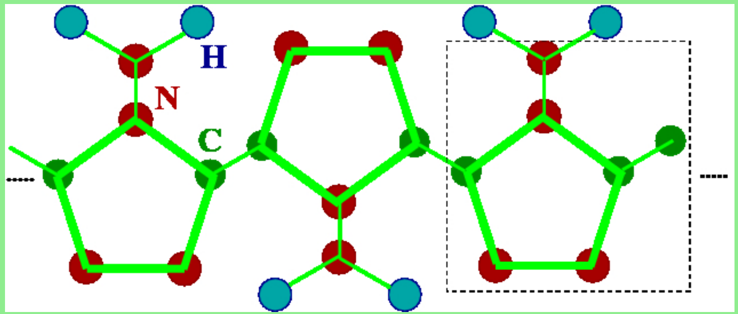
Reviews:

Z.G, D.V., Phys. Rev. B. 72, 075130 (2005),

Z.G, A.K, D.V., Progr.Theor.Phys.Suppl. 176, 1 (2008),

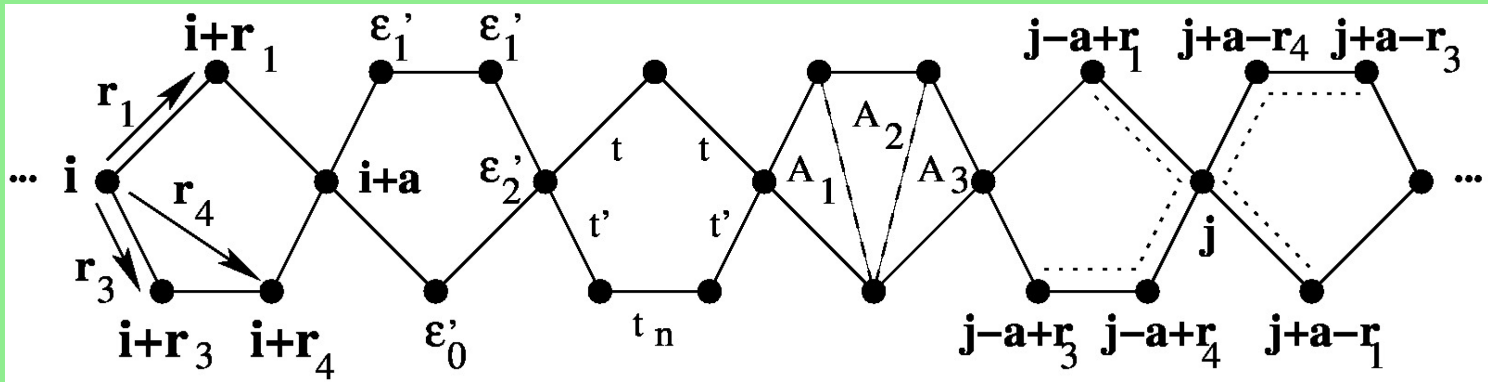
Z.G., Int. Jour. Mod. Phys. B 27, 1330009 (2013).

II. APPLICATION TO CHAIN STRUCTURES



Pentagon Chains

Case A): The Hamiltonian



$$\hat{H}_0 = \sum_{\sigma,\mathbf{i}} [\sum_{n,n',(n>n')} (t_{n,n'} \hat{c}^{\dagger}_{\mathbf{i}+\mathbf{r}_n,\sigma} \hat{c}_{\mathbf{i}+\mathbf{r}_{n'},\sigma} + H.c.) + \sum_{n=1}^{m} \epsilon_n \hat{n}_{\mathbf{i}+\mathbf{r}_n,\sigma}],$$

$$\hat{H}_U = \sum_{\mathbf{i}} \sum_{n=1}^{m} U_n \hat{n}_{\mathbf{i}+\mathbf{r}_n,\sigma} \hat{n}_{\mathbf{i}+\mathbf{r}_n,-\sigma}, \qquad \hat{H} = \hat{H}_0 + \hat{H}_U, \qquad m = 4,$$

$$U_n \geq 0, \; U_3 = U_4, \qquad \epsilon_3 = \epsilon_4, \qquad (n, n') : \; nearest \; neighbors$$

Pentagon Chains

Case A): The transformed $\widehat{H}$

$$\widehat{A}_{1,\mathbf{i},\sigma} = a_{1,1}\widehat{c}_{\mathbf{i}+\mathbf{r}_1,\sigma} + a_{1,2}\widehat{c}_{\mathbf{i},\sigma} + a_{1,3}\widehat{c}_{\mathbf{i}+\mathbf{r}_3,\sigma},$$
$$\widehat{A}_{2,\mathbf{i},\sigma} = a_{2,1}\widehat{c}_{\mathbf{i}+\mathbf{r}_1,\sigma} + a_{2,3}\widehat{c}_{\mathbf{i}+\mathbf{r}_3,\sigma} + a_{2,4}\widehat{c}_{\mathbf{i}+\mathbf{r}_4,\sigma},$$
$$\widehat{A}_{3,\mathbf{i},\sigma} = a_{3,1}\widehat{c}_{\mathbf{i}+\mathbf{r}_1,\sigma} + a_{3,4}\widehat{c}_{\mathbf{i}+\mathbf{r}_4,\sigma} + a_{3,5}\widehat{c}_{\mathbf{i}+\mathbf{a},\sigma},$$
$$\widehat{H}_0 = \sum_{\sigma}\sum_{\mathbf{i}=1}^{N_c}\sum_{m=1}^{3} \widehat{A}^{\dagger}_{m,\mathbf{i},\sigma}\widehat{A}_{m,\mathbf{i},\sigma}, \qquad \widehat{H} = \widehat{H}_0 + \widehat{H}_U.$$

where for $\epsilon'_0 = [t^2/(t'^2 t_n)](\epsilon'^2_1 - t_n^2)$**,** $\epsilon'_2 = 2t'^2/(\epsilon'_1 - t_n)$**,**
$t_n > 0, \epsilon'_1 - t_n > 0$**:**

$$a_{1,1} = e^{i\phi_1}|a_{1,1}|, \quad a_{1,2} = e^{i\phi_1}\frac{t}{|a_{1,1}|}, \quad a_{1,3} = e^{i\phi_1}\frac{t'}{t}|a_{1,1}|,$$
$$a_{2,1} = e^{i\phi_2}|a_{2,1}|, \quad a_{2,3} = -e^{i\phi_2}\frac{t'}{t}\frac{|a_{1,1}|^2}{|a_{2,1}|}, \quad a_{2,4} = -e^{i\phi_2}\frac{tt_n}{t'}\frac{|a_{2,1}|}{|a_{1,1}|^2},$$
$$a_{3,1} = e^{i\phi_3}|a_{3,1}|, \quad a_{3,4} = e^{i\phi_3}\frac{t'}{t}|a_{3,1}|, \quad a_{3,5} = e^{i\phi_3}\frac{t}{|a_{3,1}|}.$$

Pentagon Chains

Case A): The ground state wave vector

$$|\Psi_g\rangle = \prod_{\mathbf{i}=1}^{N \leq N_c} \hat{B}^\dagger_{\mathbf{i},\sigma_\mathbf{i}}|0\rangle, \qquad \{\hat{A}_{n,\mathbf{i},\sigma}, \hat{B}^\dagger_{\mathbf{i}',\sigma'_{\mathbf{i}'}}\} = 0, \qquad \hat{H}_0|\Psi_g\rangle = 0,$$

$$\begin{aligned} \hat{B}^\dagger_{\mathbf{i},\sigma} &= x_1\hat{c}^\dagger_{\mathbf{i}+\mathbf{r}_1,\sigma} + x_2\hat{c}^\dagger_{\mathbf{i},\sigma} + x_3\hat{c}^\dagger_{\mathbf{i}+\mathbf{r}_3,\sigma} + x_4\hat{c}^\dagger_{\mathbf{i}+\mathbf{r}_4,\sigma} \\ &+ y_1\hat{c}^\dagger_{\mathbf{i}-\mathbf{a}+\mathbf{r}_1,\sigma} + y_3\hat{c}^\dagger_{\mathbf{i}-\mathbf{a}+\mathbf{r}_3,\sigma} + y_4\hat{c}^\dagger_{\mathbf{i}-\mathbf{a}+\mathbf{r}_4,\sigma}, \end{aligned}$$

$$x_4 = -\frac{t}{t'}x_1, \qquad x_3 = \frac{t\epsilon'_1}{t't_n}x_1, \qquad x_2 = -\frac{t}{t'^2 t_n}(\epsilon'^2_1 - t_n^2)x_1,$$

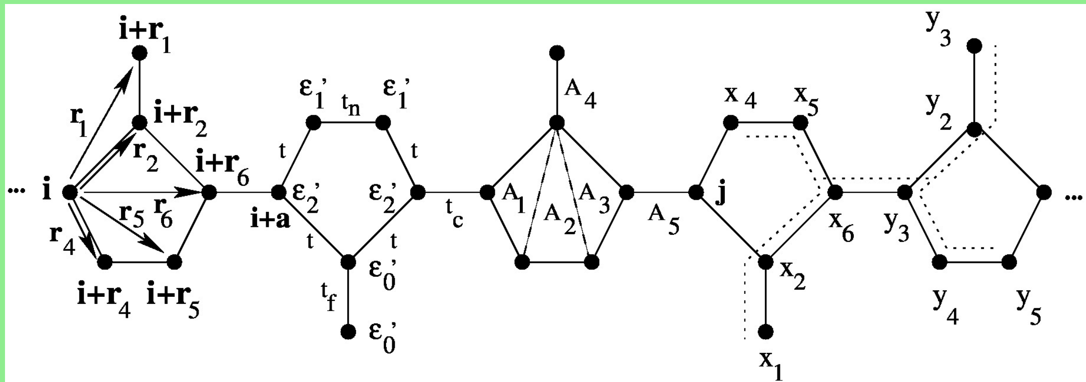
$$y_1 = x_1, \qquad y_3 = x_4 = -\frac{t}{t'}x_1, \qquad y_4 = x_3 = \frac{t\epsilon'_1}{t't_n}x_1.$$

But for: $\hat{H}_U|\Psi_g\rangle = 0$, $\sigma_\mathbf{i} = \sigma$, $\rightarrow$ $|\Psi_g\rangle = \prod_{\mathbf{i}=1}^{N=N_c} \hat{B}^\dagger_{\mathbf{i},\sigma}|0\rangle$ **.**

The ground state is ferromagnetic at $N = N_c$.

Pentagon Chains

Case B): Similar results



$$|\Psi_g\rangle = \prod_{\mathrm{i}=1}^{N=N_c} \hat{B}^\dagger_{\mathrm{i},\sigma}|0\rangle, \qquad \hat{B}^\dagger_{\mathrm{i},\sigma} = x_1[\hat{c}^\dagger_{\mathrm{i+r_1},\sigma} - \frac{\epsilon'_0}{t_f}\hat{c}^\dagger_{\mathrm{i+r_2},\sigma} + \frac{\epsilon'_0}{t_f}\hat{c}^\dagger_{\mathrm{i+r_4},\sigma} -$$

$$\frac{\epsilon'_0\epsilon'_1}{t_f t_n}\hat{c}^\dagger_{\mathrm{i+r_5},\sigma} + \frac{\epsilon'_0(\epsilon'^2_1 - t_n^2)}{t t_f t_n}\hat{c}^\dagger_{\mathrm{i+r_6},\sigma} - (\epsilon'_1 - t_n) sign(t_c) \ (\ \hat{c}^\dagger_{\mathrm{i+a+r_1},\sigma} -$$

$$\frac{\epsilon'_0}{t_f}\hat{c}^\dagger_{\mathrm{i+a+r_2},\sigma} + \frac{\epsilon'_0}{t_f}\hat{c}^\dagger_{\mathrm{i+a+r_5},\sigma} - \frac{\epsilon'_0\epsilon'_1}{t_f t_n}\hat{c}^\dagger_{\mathrm{i+a+r_4},\sigma} + \frac{\epsilon'_0(\epsilon'^2_1 - t_n^2)}{t t_f t_n}\hat{c}^\dagger_{\mathrm{i+a},\sigma} \ ) \ ].$$

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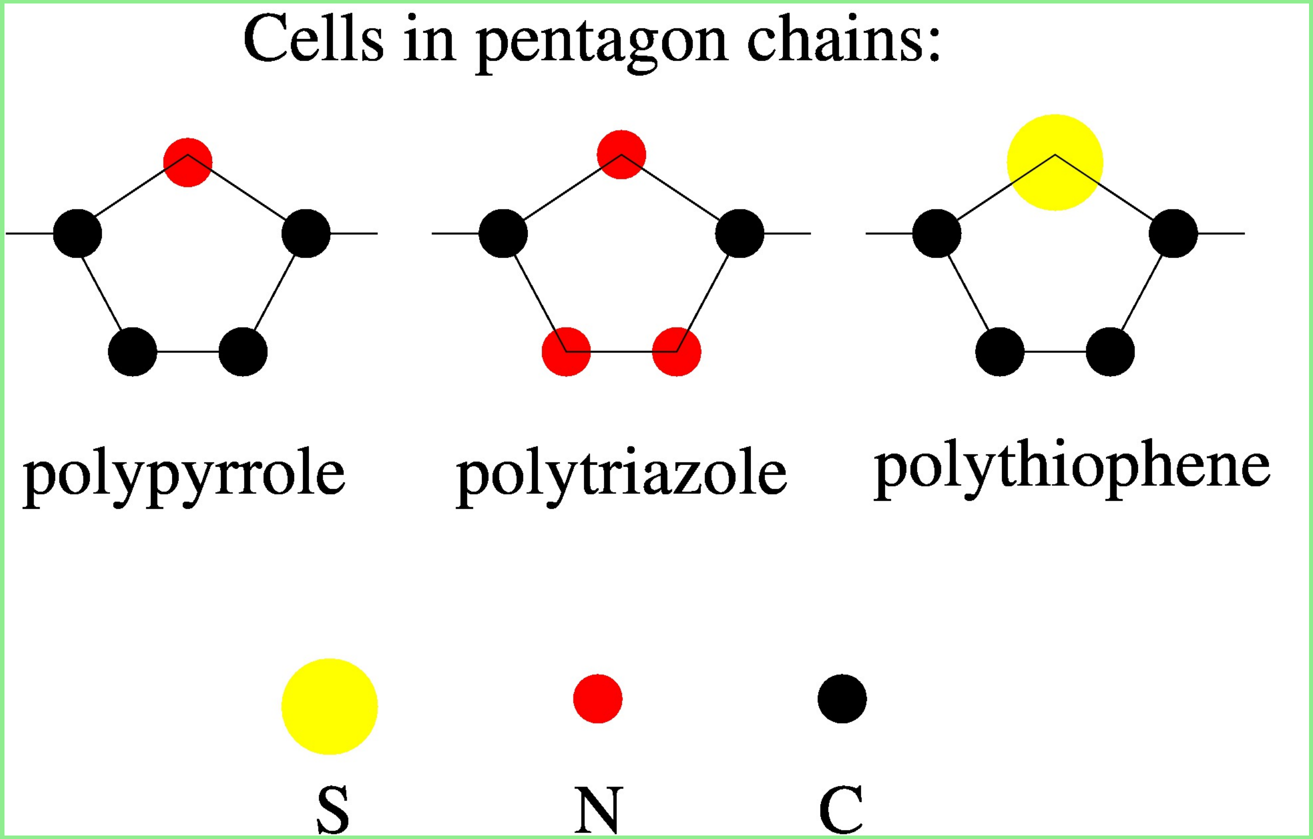
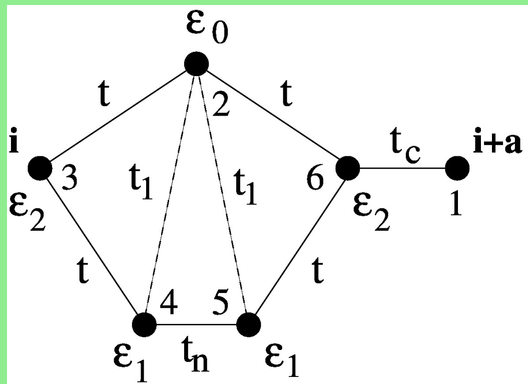


Pentagon Chains

Case C): The Hamiltonian



$$\hat{H}_0 = \sum_{\sigma,\mathbf{i}} [\sum_{n,n',(n>n')} (t_{n,n'} \hat{c}^{\dagger}_{\mathbf{i}+\mathbf{r}_n,\sigma} \hat{c}_{\mathbf{i}+\mathbf{r}_{n'},\sigma} + H.c.) + \sum_{n=1}^{m} \epsilon_n \hat{n}_{\mathbf{i}+\mathbf{r}_n,\sigma}],$$

$$\hat{H}_U = \sum_{\mathbf{i}} \sum_{n=1}^{m} U_n \hat{n}_{\mathbf{i}+\mathbf{r}_n,\sigma} \hat{n}_{\mathbf{i}+\mathbf{r}_n,-\sigma}, \qquad \hat{H} = \hat{H}_0 + \hat{H}_U, \qquad m = 5,$$

$$U_3 = U_6, \; U_4 = U_5, \qquad \epsilon_3 = \epsilon_6, \qquad \epsilon_4 = \epsilon_5, \qquad t_1 \neq 0, (n.n.n. \; hopping).$$

Pentagon Chains

Case C): The transformed $\widehat{H}$

$$\widehat{A}_{1,\mathbf{i},\sigma} = a_{1,2}\widehat{c}_{\mathbf{i}+\mathbf{r}_2,\sigma} + a_{1,3}\widehat{c}_{\mathbf{i}+\mathbf{r}_3,\sigma} + a_{1,4}\widehat{c}_{\mathbf{i}+\mathbf{r}_4,\sigma},$$
$$\widehat{A}_{2,\mathbf{i},\sigma} = a_{2,2}\widehat{c}_{\mathbf{i}+\mathbf{r}_2,\sigma} + a_{2,4}\widehat{c}_{\mathbf{i}+\mathbf{r}_4,\sigma} + a_{2,5}\widehat{c}_{\mathbf{i}+\mathbf{r}_5,\sigma},$$
$$\widehat{A}_{3,\mathbf{i},\sigma} = a_{3,2}\widehat{c}_{\mathbf{i}+\mathbf{r}_2,\sigma} + a_{3,5}\widehat{c}_{\mathbf{i}+\mathbf{r}_5,\sigma} + a_{3,6}\widehat{c}_{\mathbf{i}+\mathbf{r}_6,\sigma},$$
$$\widehat{A}_{4,\mathbf{i},\sigma} = a_{4,6}\widehat{c}_{\mathbf{i}+\mathbf{r}_6,\sigma} + a_{4,1}\widehat{c}_{\mathbf{i}+\mathbf{a},\sigma},$$
$$\widehat{H}_0 = \sum_{\sigma}\sum_{\mathbf{i}=1}^{N_c}\sum_{m=1}^{4} \widehat{A}^{\dagger}_{m,\mathbf{i},\sigma}\widehat{A}_{m,\mathbf{i},\sigma}, \qquad \widehat{H} = \widehat{H}_0 + \widehat{H}_U.$$

Conditions which must be satisfied:

$$\epsilon_0 = 2(\epsilon_1 - t_n) + \frac{(t_1 - \epsilon_1 + t_n)^2}{t_n},$$
$$\epsilon_2 = \frac{t^2}{\epsilon_1 - t_n} + \frac{t_c^2(\epsilon_1 - t_n)}{\epsilon_2(\epsilon_1 - t_n) - t^2},$$
$$\epsilon_0, \epsilon_1, \epsilon_2 > 0, \qquad t_n > 0,$$
$$\epsilon_1 - t_n > 0, \qquad \epsilon_2(\epsilon_1 - t_n) - t^2 > 0.$$

Pentagon Chains

Case C): The transformed $\hat{H}$

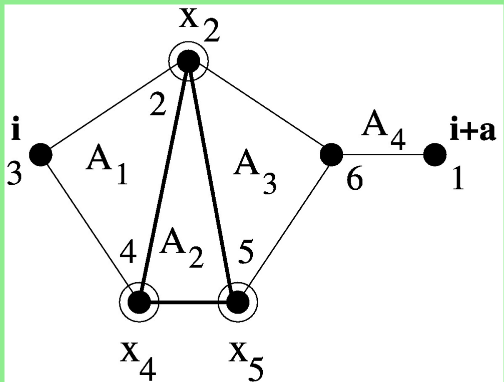
Expression of the block operator coefficients:

$$a_{1,2} = a_{1,4} = a_{3,2} = a_{3,5} = sign(t)\sqrt{\epsilon_1 - t_n}e^{i\phi_1},$$
$$a_{1,3} = a_{3,6} = \frac{|t|}{\sqrt{\epsilon_1 - t_n}}e^{i\phi_1},$$
$$a_{2,4} = a_{2,5} = \sqrt{t_n}e^{i\phi_2}, \qquad a_{2,2} = \frac{t_1 - \epsilon_1 + t_n}{\sqrt{t_n}}e^{i\phi_2},$$
$$a_{4,1} = \sqrt{\frac{\epsilon_2(\epsilon_1 - t_n) - t^2}{\epsilon_1 - t_n}}e^{i\phi_3},$$
$$a_{4,6} = t_c\sqrt{\frac{\epsilon_1 - t_n}{\epsilon_2(\epsilon_1 - t_n) - t^2}}e^{i\phi_3},$$

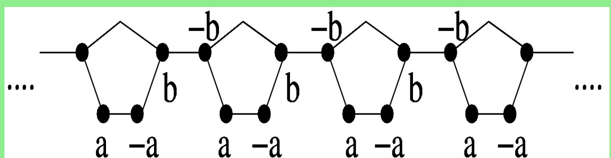
Pentagon Chains

Case C): The ground state wave vector

$$|\Psi_g\rangle = \prod_{\mathbf{i}} \hat{B}^{\dagger}_{\mathbf{i},\sigma_{\mathbf{i}}}|0\rangle, \quad \{\hat{A}_{n,\mathbf{i},\sigma}, \hat{B}^{\dagger}_{\mathbf{i}',\sigma'_{\mathbf{i}'}}\} = 0, \quad \hat{H}_0|\Psi_g\rangle = 0,$$



$$\hat{B}^{\dagger}_{\mathbf{i},\sigma_{\mathbf{i}}} = \hat{B}^{\dagger}_{\alpha_{\mathbf{i}},\sigma_{\mathbf{i}}} =$$
$$x_2\hat{c}^{\dagger}_{\mathbf{i}+\mathbf{r}_2,\sigma_{\mathbf{i}}} + x_4\hat{c}^{\dagger}_{\mathbf{i}+\mathbf{r}_4,\sigma_{\mathbf{i}}} + x_5\hat{c}^{\dagger}_{\mathbf{i}+\mathbf{r}_5,\sigma_{\mathbf{i}}},$$
$$x_4 = -a_{1,2}x_2/a_{1,4},\ x_5 = -a_{3,2}x_2/a_{3,5}.$$



$$\hat{B}^{\dagger}_{1,\sigma} = \sum_{\mathbf{i}} [a(\hat{c}^{\dagger}_{\mathbf{i}+\mathbf{r}_4,\sigma} - \hat{c}^{\dagger}_{\mathbf{i}+\mathbf{r}_5,\sigma})$$
$$+b(\hat{c}^{\dagger}_{\mathbf{i}+\mathbf{r}_6,\sigma} - \hat{c}^{\dagger}_{\mathbf{i}+\mathbf{r}_1,\sigma})],\ t_c > 0.$$

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Case C): The ground state wave vector

Because of $\widehat{H}_U|\Psi_g\rangle = 0$ one has $\sigma_{\mathbf{i}} = \sigma$ for touching operators hence

$$|\Psi_g(N_c+1)\rangle = \widehat{B}^{\dagger}_{1,\sigma} \prod_{\mathbf{i}=1}^{N_c} \widehat{B}^{\dagger}_{\mathbf{i},\sigma}|0\rangle,$$

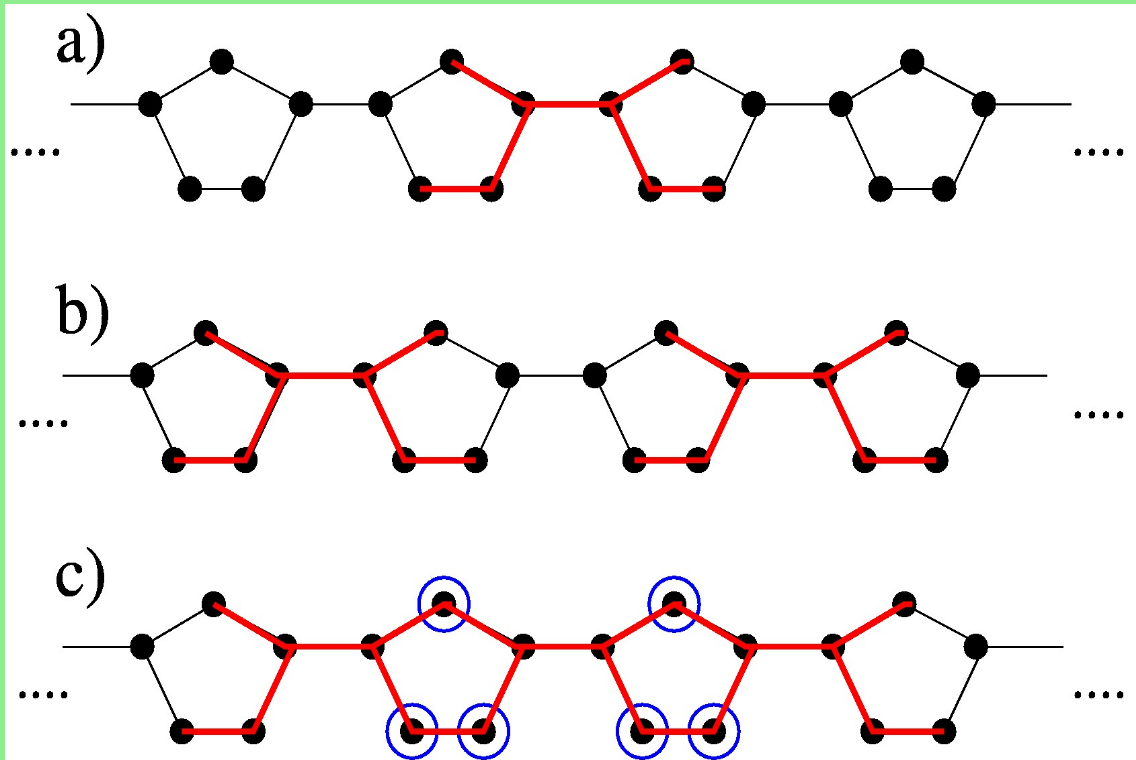
$$\begin{aligned} |\Psi_g(N_c)\rangle = \sum_{i=1}^{N_c+1} b_i\, [&\widehat{B}^{\dagger}(1,\sigma_1)B^{\dagger}(2,\sigma_2)\ldots \\ &\times \widehat{B}^{\dagger}(i-1,\sigma_{i-1})B^{\dagger}(i+1,\sigma_{i+1})\ldots \\ &\times \widehat{B}^{\dagger}(N_c,\sigma_{N_c})\widehat{B}^{\dagger}(N_c+1,\sigma_{N_c+1})]|0\rangle, \end{aligned}$$

where the set $\widehat{B}^{\dagger}_{1,\sigma}, \widehat{B}^{\dagger}_{\mathbf{i}_1,\sigma}, \widehat{B}^{\dagger}_{\mathbf{i}_2,\sigma}, \ldots \widehat{B}^{\dagger}_{\mathbf{i}_{N_c},\sigma}$, is denoted by the set $\mathcal{S} = [\widehat{B}^{\dagger}(1,\sigma), \widehat{B}^{\dagger}(2,\sigma), \ldots, \widehat{B}^{\dagger}(N_c+1,\sigma)]$.

These ground states are also ferromagnetic

Pentagon Chains

The reason for ferromagnetism, cases A,B



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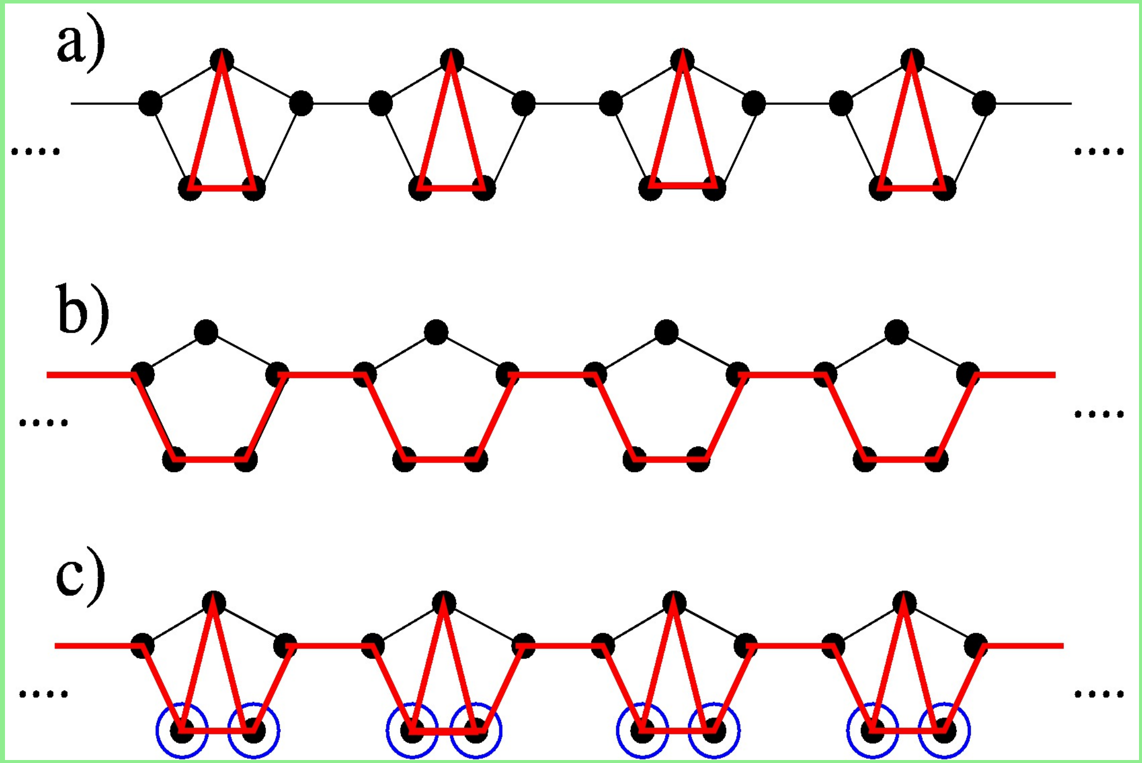
The reason for ferromagnetism, case C



Mechanism: Summary

- We are placed in the low electron concentration limit where the lowest band is partially filled.

- The lowest band is flat, the connectivity conditions inside the flat band are satisfied in cases A,B, but are missing in case C.

- Hence in cases A,B, flat band ferromagnetism is present, but such that only a small percentage of sites need to be interacting.

- In case C, since connectivity in the flat band is missing, at first wiev seems that flat band ferromagnetism is missing.

- But given by a dispersive band which touches the flat band from above, the connectivity condition is forced from the outside, hence ferromagnetism emerges.

Pentagon chains in hole doped cases

References:

Reporting papers:

M.Gulácsi, G.Kovács, Z.G., Phil.Mag.Lett.94,269,(2014).

R.Trencsényi, K.Glukhov, Z.G., Phil.Mag.94,2195,(2014).

Z. Gulácsi, European Phys. Jour. B. 87, 143, (2014).

M.Gulácsi,G.Kovács, Z.G.,Europhys.Lett.107,57005,(2014).

M.Gulácsi, G.Kovács, Z.G.,Mod.Phys.Lett.B.28,i.p.(2014).

Summary and Conclusions

- Method based on positive semidefinite operators for deducing *exact* N dependent ground states.
- The steps of the method have been presented in details: i) transcription of $\hat{H}$ in positive semidefinite form, ii) deduction of the ground states, iii) proof of uniqueness, iv) deduction of physical properties.
- The technique not depends on dimensionality or integrability hence has a large potential applicability.
- Example solutions relating physical systems: the case of the pentagon chain in the low electron concentration limit.
- The physical mechanism leading to ferromagnetism has been detailed (connectivity conditions).

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