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Lagrangian of Gross-Neveu model looks like

$$\mathcal{L} = \bar{\psi}_s i\gamma^\mu D_\mu \psi_s + \frac{G}{2N}(\bar{\psi}_s\psi_s)^2 + \frac{\sigma_s}{2} g\mu_B H \bar{\psi}_s \gamma^0 \psi_s, \qquad (1)$$

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Zeeman term can be written as

$$g = 2 \Longrightarrow \sigma_s\mu_B H\bar{\psi}^s\gamma^0\psi^s = \mu_B H\bar{\psi}^1\gamma^0\psi^1 - \mu_B H\bar{\psi}^2\gamma^0\psi^2$$

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ψ belongs to reducible represantation of SO(2,1).

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with two two-component spinors $\tilde{\psi}_1, \tilde{\psi}_2$.
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We can define two matrices γ^5 analogs of (3+1) dimensional space-time

$$\gamma^3 = \begin{pmatrix} 0\ , & I \\ I\ , & 0 \end{pmatrix}, \qquad \gamma^5 = \gamma^0\gamma^1\gamma^2\gamma^3 = i\begin{pmatrix} 0\ , & -I \\ I\ , & 0 \end{pmatrix}, \tag{4}$$

Symmetry

If there is no mass term in the Lagrangian then it is invariant under chiral symmetry

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It is occured that this symmetry can be dynamicaly broken and fermion can aquire mass

AB phase

Show that in $R^d \times S^1$ space-time vector potential along compactified dimension can not be gauged away.

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where L-length of compactified dimension.

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we will get that system interact with vector potential and not with strenght tensor of magnetic field So we call corresponding phase Aharonov-Bohm phase.

Boundary conditions

We impose the boundary contition

$$\psi(x+L) = e^{2\pi i\alpha}\psi(x) \tag{10}$$

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$\alpha = \frac{1}{2}$ -anti-periodic boundary condition

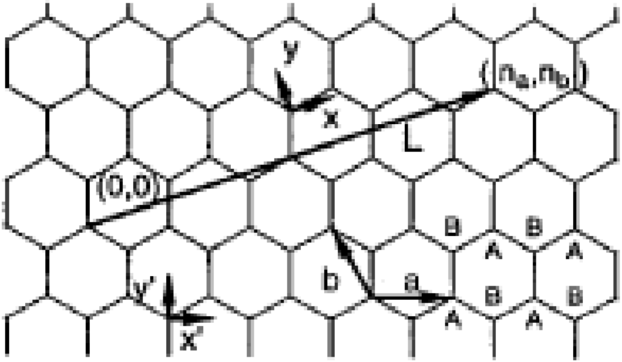


Рис.: Lattice

Boundary condition for graphene is a little more complicated, it is different for different Dirac points

$$\psi_K(x+L) = \psi_K(x) e^{2\pi i(\phi - \frac{\nu}{3})} \tag{11}$$

$$\psi_{K'}(x+L) = \psi_{K'}(x) e^{2\pi i(\phi + \frac{\nu}{3})}$$

$$\psi = \begin{pmatrix} \psi^{AK} \\ \psi^{BK} \\ \psi^{BK'} \\ \psi^{AK'} \end{pmatrix} = \frac{1}{L} \sum_{n=-\infty}^{\infty} e^{(\frac{ix}{R})(n+\phi)} \frac{1}{2\pi} \int d^2 p e^{ipx} \begin{pmatrix} \psi_n^{AK} e^{i(\frac{x}{R})\nu/3} \\ \psi_n^{BK} e^{i(\frac{x}{R})\nu/3} \\ \psi_n^{BK'} e^{-i(\frac{x}{R})\nu/3} \\ \psi_n^{AK'} e^{-i(\frac{x}{R})\nu/3} \end{pmatrix}$$

Equvalent action

$$Z(\bar{\eta},\eta) = N' \int [d\bar{\psi}][d\psi] \exp\Big(i \int (\mathcal{L} + \bar{\eta}\psi + \bar{\psi}\eta)\, d^3x\Big),$$

$$S[\bar{\psi},\psi,\sigma] = \int d^2x (i\bar{\psi}\gamma^\mu\partial_\mu\psi - \sigma\bar{\psi}\psi - \frac{N}{2G}\sigma^2) \qquad (13)$$

Perform Hubbard-Stratonovich transformation

$$Z(\bar{\eta},\eta) = \int D[\bar{\psi}(x)]D[\psi(x)]e^{iS[\bar{\psi},\psi]} = \qquad (14)$$

$$= \int D[\bar{\psi}(x)]D[\psi(x)]D[\sigma(x)]e^{iS[\bar{\psi},\psi,\sigma]}$$

Auxiliary Lagrangian has the form

$$\mathcal{L}(\bar{\psi},\psi,\sigma]) = i\bar{\psi}\gamma^\mu\partial_\mu\psi - \sigma\bar{\psi}\psi - \frac{N}{2G}\sigma^2. \qquad (15)$$

Euler-Lagrange equation for scalar field is

$$\sigma = -\frac{G}{N}\bar{\psi}\psi. \qquad (16)$$

$$Z[\eta,\bar{\eta},J] = \int D[\psi(x)]D[\bar{\psi}(x)]D[\sigma(x)]\exp\left(i\int dx\mathcal{L}(\bar{\psi},\psi,\sigma) + \int dx\bar{\eta}\psi + \int dx\bar{\psi}\eta + \int dx\,\sigma J\right) \quad (17)$$

$N : J = O(N)$.

Integrate over fermion fields we obtain

$$Z[\eta,\bar{\eta},J] = \int D[\sigma(x)]\exp\left(iN\int dx\left(-\frac{1}{2G}\sigma^2 - itr\ln D - \frac{1}{N}\bar{\eta}D^{-1}\eta\right) + + \int dx\,\sigma J\right)$$

$$\langle\sigma\rangle = -iGtr\frac{1}{i\gamma\partial - \sigma} + J + \frac{1}{N}\bar{\eta}\eta, \quad (19)$$

Generating functional of connected Green functions are

$$e^{\mathrm{i}W(\bar{\eta},\eta,J)} = Z(\bar{\eta},\eta,J) = N' \int [d\bar{\psi}][d\psi] \exp\Big(i \int (\mathcal{L}+\bar{\eta}\psi+\bar{\psi}\eta+\sigma J)\, d^3x\Big),$$

Definition of classical average fields are

$$\sigma(x) = \frac{\delta W}{\delta J(x)} = \langle \sigma \rangle + o\left(\frac{1}{N}\right) \tag{20}$$

$$\psi(x) = \frac{\delta W}{\delta \bar{\eta}(x)} = D^{-1}\eta \tag{21}$$

$$\bar{\psi}(x) = \frac{\delta W}{\delta \eta(x)} = -\bar{\eta} D^{-1} \tag{22}$$

having performed Legandre transformation effective action could be derived

$$\Gamma[\psi, \bar{\psi}, \sigma] = W[\eta, \bar{\eta}, J] - \int \bar{\psi}\eta - \int \bar{\eta}\psi - \int \sigma J = \tag{23}$$

$$\Gamma[\psi,\bar{\psi},\sigma] = \int dx \left(\bar{\psi}\gamma^\mu\partial_\mu\psi - \sigma\bar{\psi}\psi - \frac{N}{2G}\sigma^2 - iNtr\ln(i\gamma\partial - \sigma) \right) \quad (24)$$

$$\frac{\delta\Gamma}{\delta\psi} = \bar{\eta}, \quad \frac{\delta\Gamma}{\delta\bar{\psi}} = -\eta, \quad \frac{\delta\Gamma}{\delta\sigma} = -J \quad (25)$$

Taking the sources to null we get vev of the $\psi, \bar{\psi}, \sigma$ fields satisfying condition of extremum of efectivef potential

$$\frac{\delta\Gamma}{\delta\psi} = 0, \quad \frac{\delta\Gamma}{\delta\bar{\psi}} = 0, \quad \frac{\delta\Gamma}{\delta\sigma} = 0 \quad (26)$$

For fermions we get Dirac equation

$$i\gamma^\mu\partial_\mu\psi - \sigma\psi = 0 \quad (27)$$

Suppose in oreder to maintain Lorentz invariance that $\psi = 0, \ \bar{\psi} = 0$.

Effective potential

We obtain the effective action of field

$$\Gamma[\sigma] = \int dx \left(-\frac{N}{2G}\sigma^2 - iNtr\ln(i\gamma\partial - \sigma) \right) \tag{28}$$

Defining effective potential as

$$V_{\text{eff}} = -\frac{\Gamma}{\int d^3x} = -\frac{\Gamma}{TV}$$

$$V_{\text{eff}} = \frac{N}{2G}\sigma^2 + i\frac{1}{TV}Ntr\ln(i\gamma\partial - \sigma) \tag{29}$$

$$V_{eff} = \frac{\sigma^2}{2G} - \frac{1}{\beta L} \sum_s \sum_{n=-\infty}^{\infty} \times \qquad (30)$$

$$\times \int_{-\infty}^{\infty} \frac{dp}{2\pi} \ln \left[p_0^2 + \left(\frac{2\pi}{L} \right)^2 (n + \phi + \alpha)^2 + p_1^2 + \sigma^2 \right].$$

$$\phi = \frac{eL^2 H}{8\pi^2}$$

magnetic flux

To consider theory at finite temperature and density we need to substitute integration to summation over Matsubara frequencies

$$p \to \frac{2\pi}{\beta}\left(l+\frac{1}{2}\right) - i\mu, \quad \int\limits_{-\infty}^{\infty} \frac{dp_0}{2\pi} \to \frac{1}{\beta}\sum_{n=-\infty}^{\infty} \tag{31}$$

Eff potential at finite temperature is

$$V_{eff} = \frac{\sigma^2}{2G} - \frac{1}{\beta L}\sum_{s}\sum_{l}\sum_{n=-\infty}^{\infty} \times \tag{32}$$

$$\times \int\limits_{-\infty} \frac{dp_1}{2\pi} \ln\left[\left(\frac{2\pi}{\beta}\left(l+\frac{1}{2}\right) - i\mu_s\right)^2 + \left(\frac{2\pi}{L}\right)^2 (n+\phi)^2 + p_1^2 + \sigma^2\right].$$

There is a very usefull formula, using it we can separate contribution of compactification

$$\sum_{n=-\infty}^{\infty} \ln(1+\frac{b^2}{(n+\alpha)^2+a^2}) = \tag{33}$$

$$\sum_{n=-\infty}^{\infty} (\ln((n+\alpha)^2+a^2+b^2) - \ln((n+\alpha)^2+a^2)) = \tag{34}$$

$$= \int_{-\infty}^{\infty} d\tau \ln(1+\frac{b^2}{\tau^2+a^2}) +$$

$$\ln \frac{1-2\cos(2\pi\alpha)e^{-2\pi\sqrt{a^2+b^2}}+e^{-4\pi\sqrt{a^2+b^2}}}{1-2\cos(2\pi\alpha)e^{-2\pi\sqrt{a^2}}+e^{-4\pi\sqrt{a^2}}}$$

Effective potential could be obtained in the relatively short form

$$V_{\text{eff}} = \frac{N}{\pi}\left(\frac{\sigma^3}{3} - \frac{\sigma^2\sigma_0}{2}\right) + V_{\mu T} + \tag{35}$$

$$+\frac{4N}{\beta L}\sum_{n=1}^{\infty}\sum_{l=-\infty}^{\infty}\frac{\sigma_l}{n}K_1(L\sigma_l n)\cos(2\pi\alpha n)$$

where is used the notation

$$\Delta_l = \sqrt{\left(\frac{2\pi}{\beta}\left(l+\frac{1}{2}\right) - i\mu\right)^2 + \Delta^2}$$

$K_\mu(x)$ modified Bessel function of the second kind

Contribution due to finite temperature and chemical potential is given by

$$V_{\mu T} = -\frac{N}{\pi\beta^3} Li_3(-e^{-\beta\sigma+\beta\mu}) + -\frac{N}{\pi\beta^3} Li_3(-e^{-\beta\sigma-\beta\mu}) + \tag{36}$$

$$-\frac{N\sigma}{\pi\beta^2} Li_2(-e^{-\beta\sigma+\beta\mu}) + -\frac{N\sigma}{\pi\beta^2} Li_2(-e^{-\beta\sigma-\beta\mu}) = \tag{37}$$

where polilogarithm was used which is defined

$$Li_\nu(z) = \sum_{k=1}^{\infty} \frac{z^k}{k^\nu} \tag{38}$$

We need renormalization of the coupling constant

$$\frac{1}{g(\mu)} = \frac{1}{G} - \frac{\Lambda}{\pi} + \frac{\mu}{\pi^2} = \frac{1}{g} + \frac{\mu}{\pi^2}. \tag{39}$$

Running of the coupling

$$\frac{1}{g(\mu)} = \frac{1}{g(\mu_0)} + \frac{1}{\pi^2}(\mu - \mu_0). \tag{40}$$

$$V_{\text{eff}} = V_L + V_0 + V_{\mu T} \tag{41}$$

$$V_L = 2Re\left(\frac{1}{\pi L^3} Li_3(e^{-L\sigma+2\pi i\phi}) + \frac{\sigma}{\pi L^2} Li_2(e^{-L\sigma+2\pi i\phi})\right) \tag{42}$$

$$V_0 = \frac{N}{\pi}\left(\frac{\sigma^3}{3} - \frac{\sigma^2\sigma_0}{2}\right) \tag{43}$$

$$V_{\mu T} = -\frac{2}{\beta L}\sum\int \frac{dp_1}{2\pi}\left(\ln(1+e^{\beta E^+_{np_1}}) + \ln(1+e^{\beta E^-_{np_1}})\right) \tag{44}$$

$$E^{\pm}_{np_1} = E_{np_1} \pm \mu \tag{45}$$

$$V_{\rm eff} = \frac{N}{\pi}(\frac{\sigma^3}{3} - \frac{\sigma^2\sigma_0}{2}) + \frac{2N}{\pi L^3} Li_3(e^{-L\sigma+2\pi\alpha}) + \frac{2N}{\pi L^3} Li_3(e^{-L\sigma-2\pi i\alpha}) + \tag{46}$$

$$\frac{2N\sigma}{\pi L^2} Li_2(e^{-L\sigma+2\pi i\alpha}) + + \frac{2N\sigma}{\pi L^2} Li_2(e^{-L\sigma-2\pi i\alpha})$$

$$-\frac{2N}{\pi\beta L}\sum_{\sigma_n<\mu}\int\frac{dp_1}{2\pi}\ln\left(1+\mathrm{e}^{(-\beta\sqrt{\mathrm{p}_1^2+\Delta_\mathrm{n}^2}+\beta\mu)}\right)+$$

$$+\frac{2N}{\pi\beta L}\sum_{\sigma_n>\mu}\sum_{m=1}^{\infty}(-1)^m\frac{\sigma_n}{m}K_1(\beta\sigma_n m)\mathrm{e}^{\beta\mu\mathrm{m}}$$

$$+\frac{2N}{\pi\beta L}\sum_{n=-\infty}^{\infty}\sum_{m=1}(-1)^m\frac{\sigma_n}{m}K_1(\beta\sigma_n m)e^{-\beta\mu m}$$

where $\Delta_n = \sqrt{(\frac{2\pi}{L})^2(n+\alpha)^2+\sigma^2}$

Full magnetization is given by

$$m = -\left(\frac{\partial V_{eff}}{\partial \mu}\frac{g\mu_B}{2} + \frac{\partial V_{eff}}{\partial \phi}\frac{eL^2}{8\pi^2}\right) \tag{47}$$

$$n_s = \frac{1}{L}\sum_{n=-\infty}^{\infty}\int \frac{dp_1}{2\pi}\left(\frac{\mathrm{sh}(\beta\mu_s)}{\mathrm{ch}(\beta\mu_{s)} + \mathrm{ch}(\beta E_{np_1})}\right) \tag{48}$$

where

$$E_{np_1} = \sqrt{p_1^2 + \left(\frac{2\pi}{L}\right)^2 (n+\alpha)^2 + \sigma^2}$$

Magnetization is given by

$$m = \mu_B(n_1 - n_2)$$

Representation of spinors

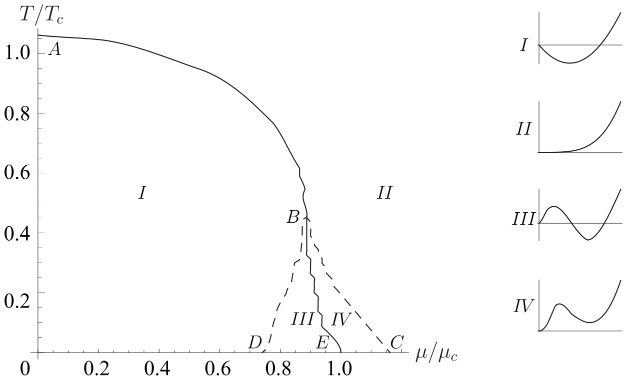
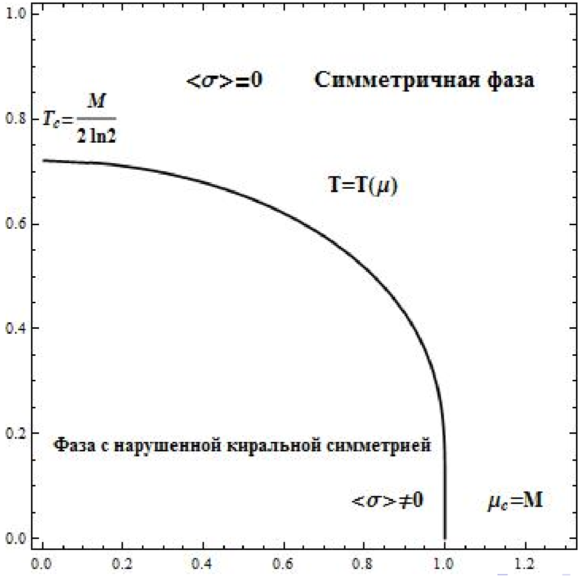


Рис.: T-μ phase diagram for L=1.2L_c

Plots



1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
<σ>=0
Симметричная фаза
$T_c = \frac{M}{2 \ln 2}$
T=T(μ)
Фаза с нарушенной киральной симметрией
<σ>≠0
μ_c=M

Plots

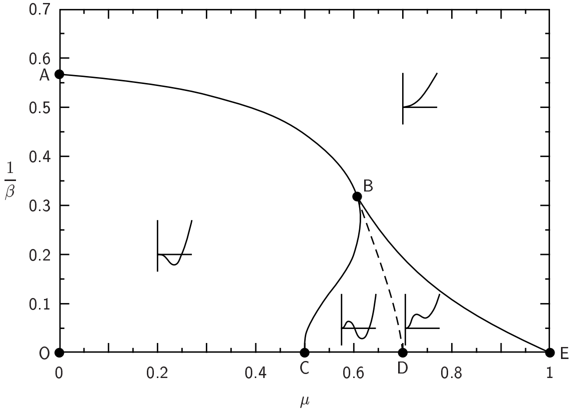


Рис.:

plots

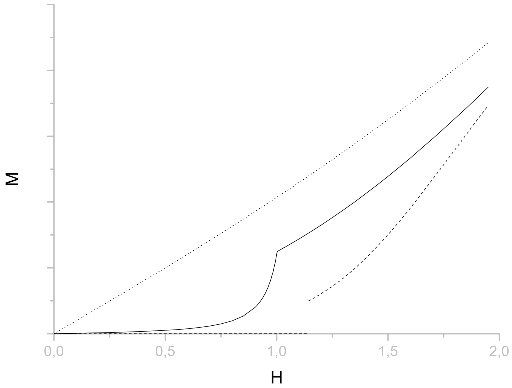


Рис.: Dependence of Zeeman magnetization on magnetic field T=$\frac{1}{3}T_c$(dashed line), T=$\frac{4}{5}T_c$ (solid line), T=$\frac{3}{2}T_c$(dotted line)

Plots

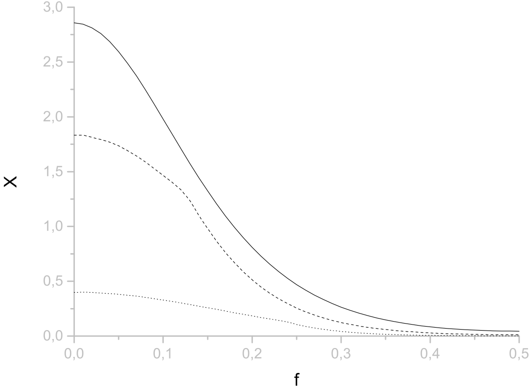


Рис.: magnetic susceptibility on flux $T = 3/2T_c$ (solid line), $T = 5/4T_c$ (dashed line). T $= T_c$ (dotted line)

Plots

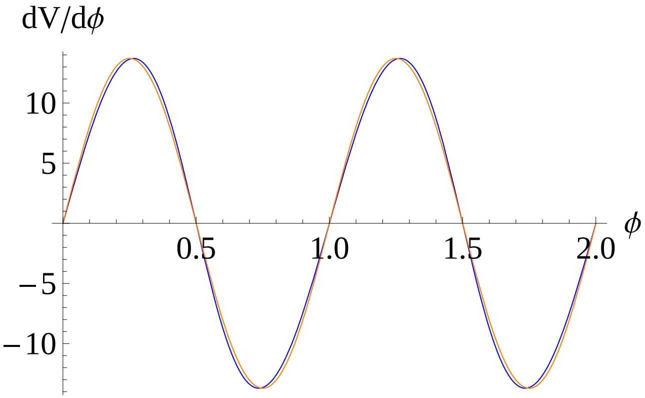


Рис.: Aharonov-Bohm magnetization on flux $L >> L_c, \beta >> \beta_c$

Plots

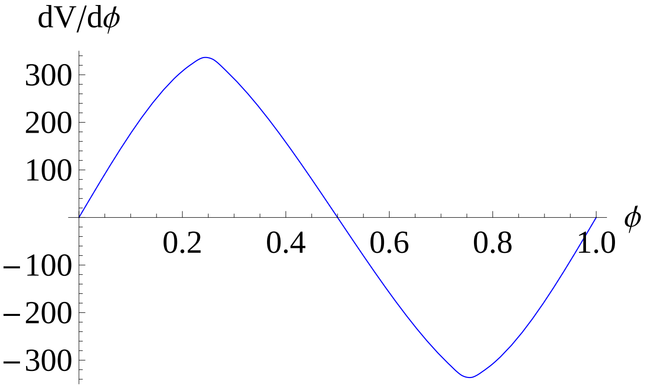


Рис.: AB magnetization on magnetic flux $L = 0,5L_c$, $\beta = 3\beta_c$

Plots

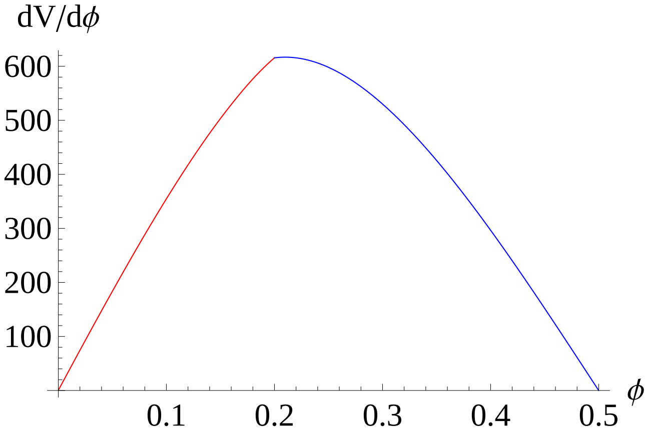


Рис.: T-μ phase diagram for L=1.2L_c

Plots

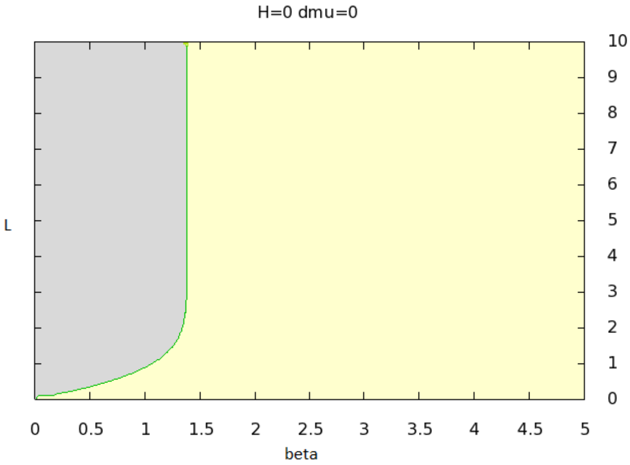


Рис.: L -T phase diagram for H=0

Plots

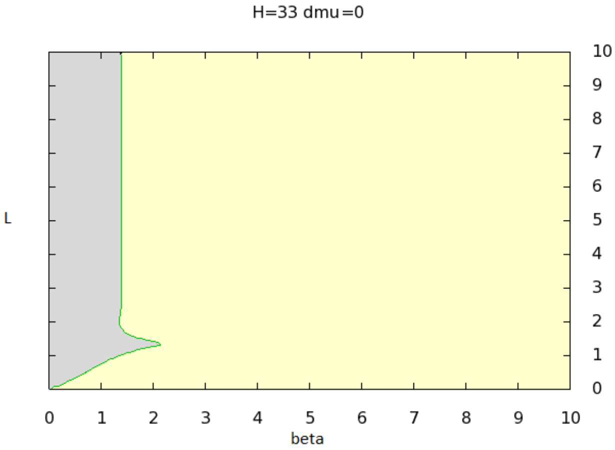


Рис.: L -T phase diagram for H=33

Plots

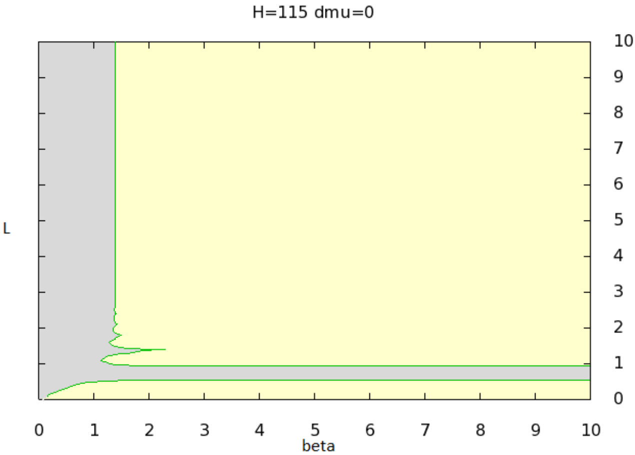


Рис.: L -T phase diagram for H=115

Plots

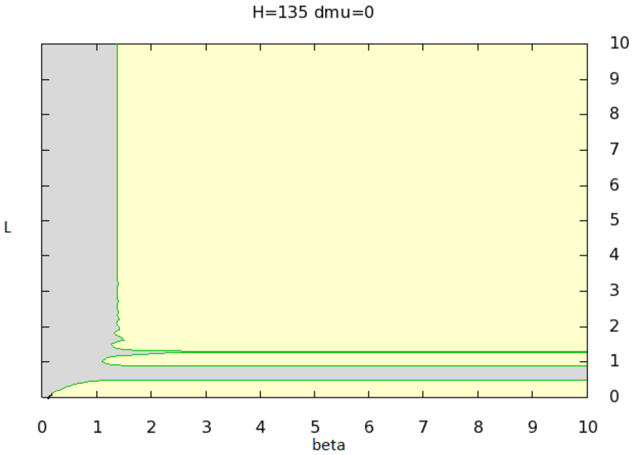


Рис.: L -T phase diagram for H=135

Plots

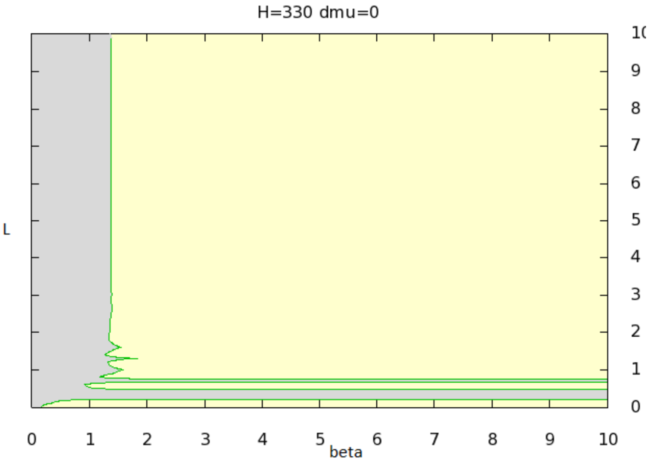


Рис.: L -T phase diagram for H=0

Plots

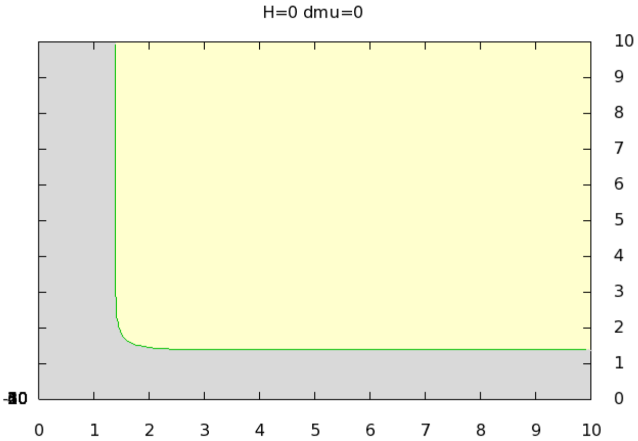


Рис.: L -T phase diagram for H=0, $\alpha = \frac{1}{2}$

Plots

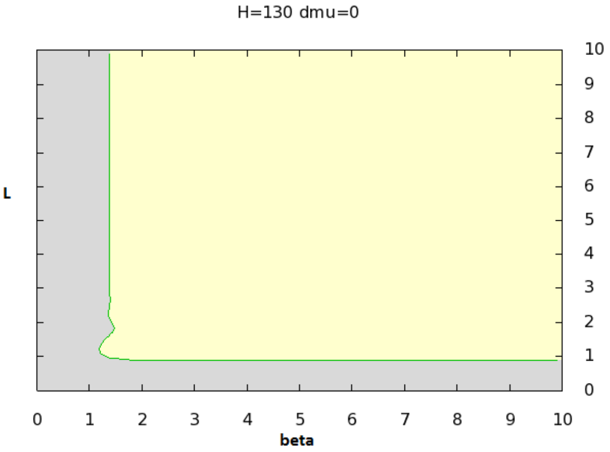


Рис.: L -T phase diagram for H=130, $\alpha = \frac{1}{2}$

Plots

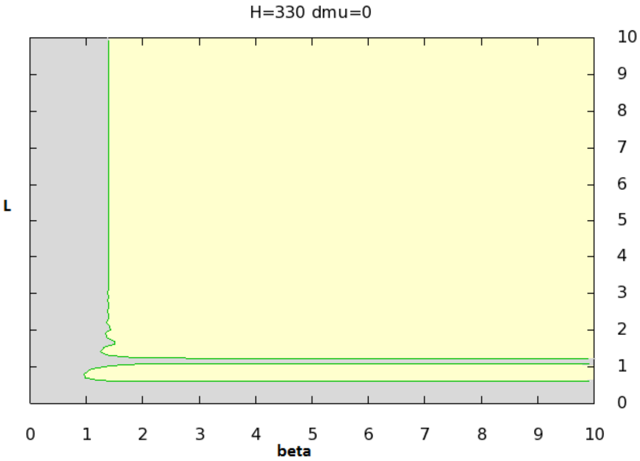


Рис.: L -T phase diagram for H=330, $\alpha = \frac{1}{2}$

Summary

Gross-Neveu model with one compactified spatial dimension (i.e., a cylinder) under the infl uence of the magnetic feld parallel to the axis of the cylinder with consideration for the fnite temperature and chemical potential.

Two Zeeman interaction with spins of the electrons and AB phase due to flux through cylinder can be accounted for in (2+1)

We hope this result can shed light on carbon nanotubes under influence of external magnetic field

Summary

Thanks for the attention