Phase diagram and thermodynamics for asymmetric planar fermionic systems in the presence of external fields

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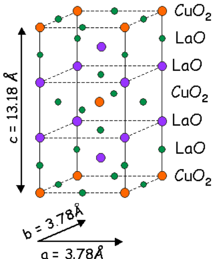
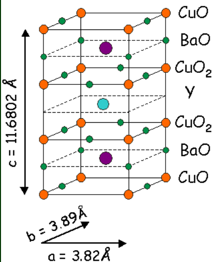
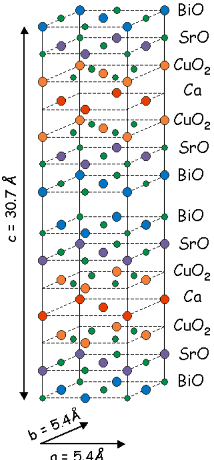
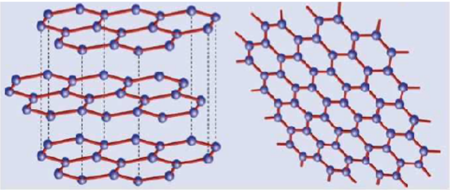
Planar Systems in Physics

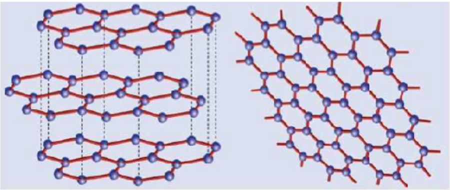
Many condensate matter systems can be approximated as two-dimensional, like metal and conducting organic (polyacetylene) films, graphene and high-T superconductors (La(2-x)Sr(x)CuO2, YBCO, BSCCO):











It is possible to describe these planar systems in condensed-matter physics through quantum field theory models and techniques for fermions in $2+1$ dimensions [Nambu-Jona-Lasinio (NJL) or Gross-Neveu (GN) type of models are simple examples]

Describing interacting two-dimensional fermionic systems in quantum field theory

$$\mathcal{L}[\bar{\Psi},\Psi] = \sum_{s=\uparrow,\downarrow} \bar{\Psi}_s(i\hbar\partial_t - i\hbar v_F \vec{\gamma}\cdot\vec{\nabla})\Psi_s + \sum_{s=\uparrow,\downarrow} \frac{\lambda}{2N}\hbar v_F (\bar{\Psi}_s\Psi_s)^2$$

Properties:

- describes self-interacting fermions with N flavors
- It is asymptotically free
- Exactly soluble model (mean-field)
- In 2+1d it is renormalizable in the 1/N expansion
- Mass terms (which violate chiral symmetry explicitly) can be included as well without loss of solvability (at large N)
- guide to thermodynamics of chiral symmetry restoration in QCD[1]

[1] Kneur, Pinto and ROR, PRD74, 1252020 (2006), Kneur, Pinto, ROR, Staudt, PRD76, 045020 (2007), Kneur, Pinto and ROR, PRC81, 065205 (2010)

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- It can have either discrete or a continuous chiral symmetry
- At finite T only version of the model (in 2+1d, massless) with discrete chiral symmetry undergoes PT (no continuous PT in 2 space dim)
- Both chiral and superconducting gaps can be implemented
- Useful model to describe low energy (condensed matter) systems as well[2] (continuum version of the Su-Shrieffer-Heeger model for polyacetylene in 1d)

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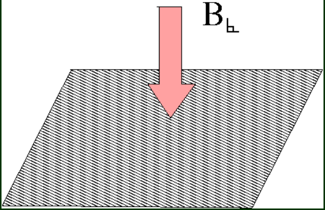
Applying an external magnetic field $\vec{B}$

The application of an external magnetic field, $\vec{A} = (0, x\, B_{\perp}, 0)$:



- The perpendicular B field couples to the fermions orbital motion – Landau levels for fermions in a magnetic field;
- Most well known case, studied by many authors[3];
- Chiral symmetry breaking for both positive coupling and negative coupling cases (for the positive coupling case, chiral symmetry breaking for any finite B field – magnetic catalysis);
- B field tends to strengthen the symmetry broken phase, e.g. higher critical temperature in the presence of perpendicular B.

[3] Klimenko (1992), Gusynin, Miransky, Shovkovy (1994), (1996), etc

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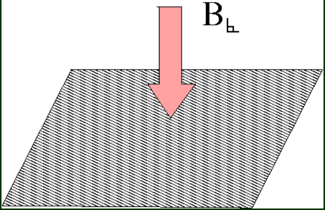

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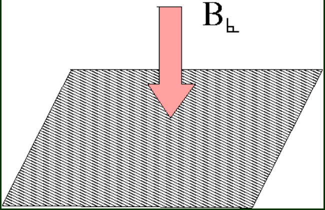

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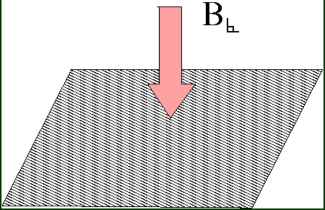

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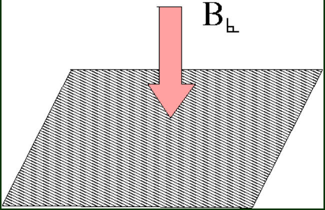

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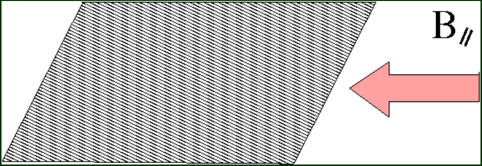

- The parallel (in-plane) B field couples only to the spins of fermions – intrinsic Zeeman effect;
- The least studied case in field theory[4], but common in condensed matter systems;
- Chiral symmetry breaking only for attractive interaction;
- parallel B field tends to weaken the symmetry broken phase (e.g. smaller critical temperature in the presence of in-plane B).

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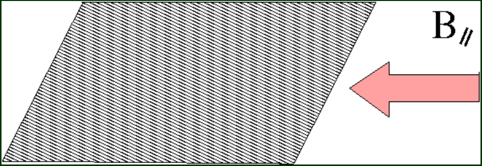

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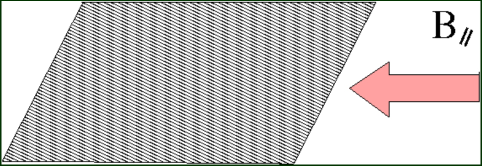

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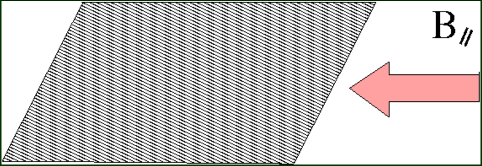

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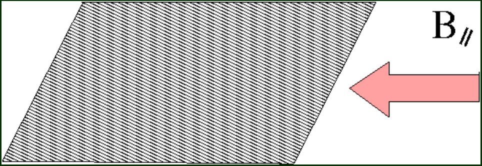

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Effective Potential

Grand canonical partition function:

$$Z = \int D\Delta \prod_s D\psi^\dagger D\psi \, \exp\left\{-S_E[\bar{\psi},\psi,\Delta]\right\},$$

$$S_E[\bar{\psi},\psi,\Delta] = \int_0^{\hbar\beta} d\tau \int d^2x \, \left\{ \sum_{s=\uparrow,\downarrow} \bar{\psi}^s \left[\hbar\partial_\tau \right.\right.$$
$$+ i\hbar v_F \gamma_1 \left(\partial_x + i\frac{e}{c} A_x\right) + i\hbar v_F \gamma_2 \left(\partial_y + i\frac{e}{c} A_y\right)$$
$$\left.\left. + \Delta + \gamma_0 \mu + \frac{\sigma_s}{2}\gamma_0 \, g_{\mathrm{Lande}} \, \mu_{\mathrm{Bohr}} B_\parallel \right] \psi^s + \frac{N}{2\hbar v_F \lambda}\Delta^2 \right\},$$

$A_x = 0, \; A_y = x B_\perp$

In-plane magnetic field $B_{\|} \neq 0$

The Zeeman energy term is like an effective chemical potential:

$$\sum_{s=\uparrow,\downarrow} \mu_s \bar{\psi}^s \gamma_0 \psi^s = \sum_{s=\uparrow,\downarrow} \left(\mu + \frac{\sigma_s}{2} g_{\rm Lande}\, \mu_{\rm Bohr} B_{\|} \right) \bar{\psi}^s \gamma_0 \psi^s = \mu_\uparrow {\psi^\uparrow}^\dagger \psi^\uparrow + \mu_\downarrow {\psi^\downarrow}^\dagger \psi^\downarrow \,,$$

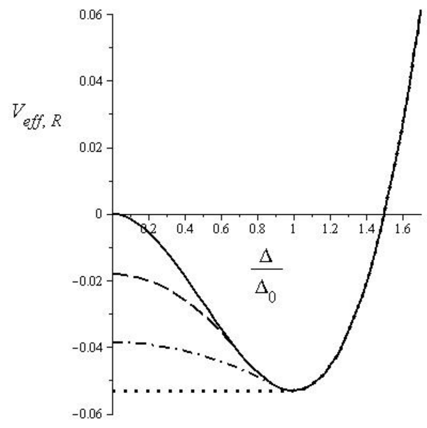
$\mu_\uparrow = \mu + \delta\mu$, and $\mu_\downarrow = \mu - \delta\mu$, with $\delta\mu = g_{\rm Lande}\, \mu_{\rm Bohr} B_{\|}/2$.

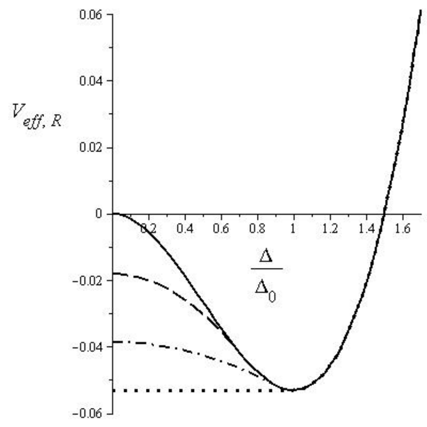
μ can be interpreted as to account for the extra density of electrons that is supplied to the system by the dopants, while $\delta\mu$ measures the amount of asymmetry introduced and it is directly proportional to the in-plane applied external magnetic field.

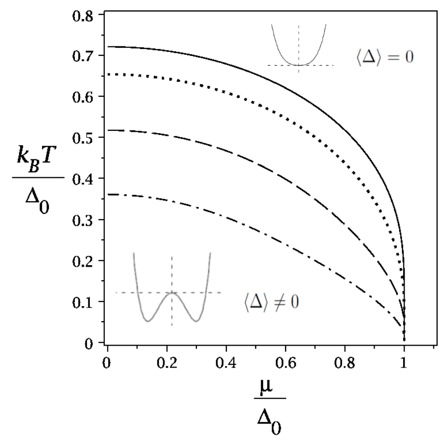
The effective potential for $B_\parallel \neq 0$, $B_\perp = 0$

$$
\frac{1}{N} V_{\mathrm{eff,R}}(\Delta_c, T, \mu_\uparrow, \mu_\downarrow) = \frac{1}{2\hbar v_F \lambda_R} \Delta_c^2 + \frac{1}{\pi(\hbar v_F)^2} \left(\frac{|\Delta_c|^3}{3} - \Delta_0 \Delta_c^2 \right)
+ \frac{|\Delta_c|}{2\pi\beta^2} \left\{ \mathrm{Li}_2[-e^{-\beta(\Delta_c - \mu_\uparrow)}] + \mathrm{Li}_2[-e^{-\beta(\Delta_c + \mu_\uparrow)}] \right\}
+ \frac{1}{2\pi\beta^3} \left\{ \mathrm{Li}_3[-e^{-\beta(\Delta_c - \mu_\uparrow)}] + \mathrm{Li}_3[-e^{-\beta(\Delta_c + \mu_\uparrow)}] \right\} + (\mu_\uparrow \to |\mu_\downarrow|)
$$

$$
\Delta_0 = \frac{\hbar v_F \pi}{\lambda_R} , \quad \frac{1}{\lambda_R} = \frac{\hbar v_F}{N} \frac{d^2 V_{\mathrm{eff}}(\Delta_c)}{d\Delta_c^2}\Big|_{\Delta_c = \Delta_0}
$$


0.06
0.04
0.02
0
−0.02
−0.04
−0.06
$V_{eff,\,R}$
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6
$\frac{\Delta}{\Delta_0}$

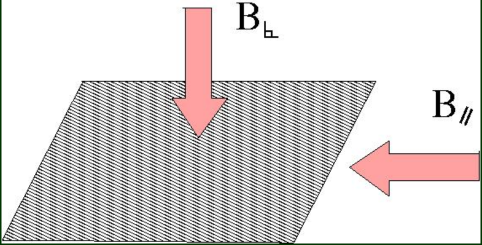




critical chemical potential $\mu_c = \Delta_0$. For $\delta\mu \geq \mu_c$, $\langle\Delta\rangle = 0$.
Magnetic properties for the spin asymmetric system studied in
Caldas and ROR, PRB80, 115428 (2009)

$B_{\parallel} \neq 0$ and $B_{\perp} \neq 0$

With $B_{\parallel} \neq 0$ and $B_{\perp} \neq 0$, $\vec{A} = (0, x\,B_{\perp},\; y\,B_{\parallel})$,



Dispersion energy (in two space dimensions) for fermions with $\mathbf{p}^2 \to (2k+1-s)eB_{\perp}$, $s = \pm 1$, $k = 0{,}1{,}2,\ldots$ (Landau levels),

$$\int \frac{d^3 q_E}{(2\pi)^3} \to \frac{eB_{\perp}}{2\pi}\frac{1}{\beta}\sum_n \sum_k$$

$n = 0, \pm 1, \pm 2, \ldots$, sum over Matsubara's frequencies for fermions, $\omega_n = (2n+1)\pi/\beta$.

The effective potential for $B_\parallel \neq 0$, $B_\perp \neq 0$

$$
\begin{aligned}
\frac{1}{N} V_{\rm eff,R}(\beta,\mu_\uparrow,\mu_\downarrow,\Delta_c) &= \frac{\Delta_c^2}{2\lambda_R} + \Delta_c^2 \frac{|eB_\perp|^{1/2}}{2\sqrt{2}\pi} \zeta\left(\frac{1}{2}, \frac{\Delta_0^2}{2|eB_\perp|}\right) \\
&- \frac{\Delta_0^2\Delta_c^2}{4\sqrt{2}\pi|eB_\perp|^{1/2}} \zeta\left(\frac{3}{2}, \frac{\Delta_0^2}{2|eB_\perp|}\right) - \frac{\sqrt{2}|eB_\perp|^{3/2}}{\pi} \zeta\left(-\frac{1}{2}, \frac{\Delta_0^2}{2|eB_\perp|} + 1\right) \\
&- \frac{|eB_\perp|}{4\pi\beta} \left\{ \ln\left(1 + e^{-\beta(\Delta_c - \mu_\uparrow)}\right) + \ln\left(1 + e^{-\beta(\Delta_c - |\mu_\downarrow|)}\right) \right. \\
&+ 2\sum_{k=1}^{\infty} \ln\left(1 + e^{-\beta\left(\sqrt{\Delta_c^2 + 2k|eB_\perp|} - \mu_\uparrow\right)}\right) \\
&+ 2\sum_{k=1}^{\infty} \ln\left(1 + e^{-\beta\left(\sqrt{\Delta_c^2 + 2k|eB_\perp|} - |\mu_\downarrow|\right)}\right) \\
&\left. + (\mu_\uparrow \to -\mu_\uparrow, |\mu_\downarrow| \to -|\mu_\downarrow|) \right\}
\end{aligned}
$$

$\mu_\uparrow = \mu + \delta\mu$, and $\mu_\downarrow = \mu - \delta\mu$, with $\delta\mu = g_{\rm Lande}\, \mu_{\rm Bohr} B_\parallel / 2$.

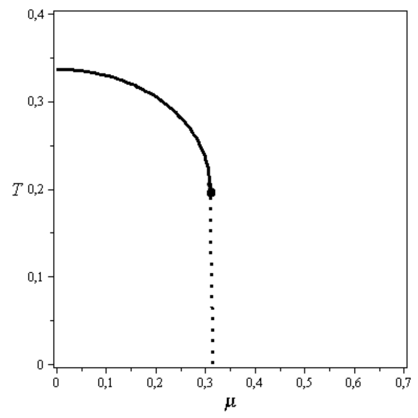
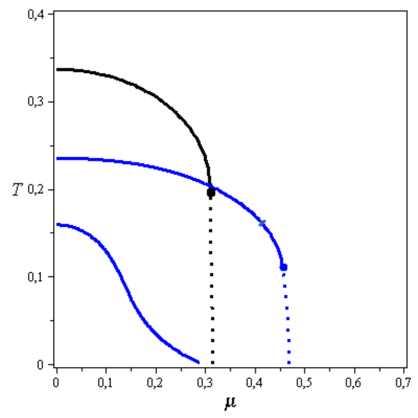


Figure: Phase diagram for fixed $eB_{\perp} = 0.5\Delta_0^2$. Black: $\delta\mu = 0.0$; blue: $\delta\mu = 0.3\Delta_0$; and green: $\delta\mu = 0.5\Delta_0$.



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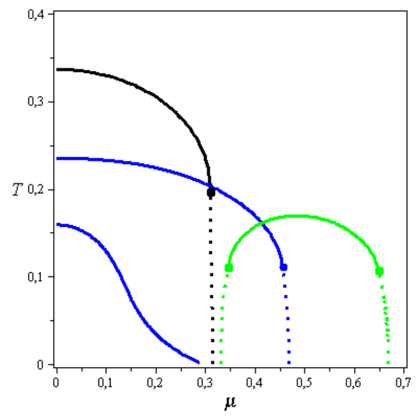

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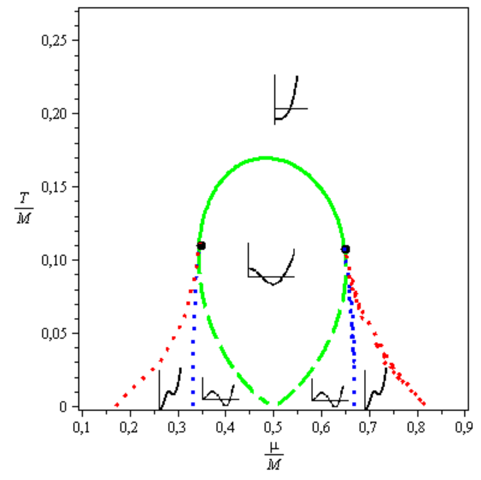
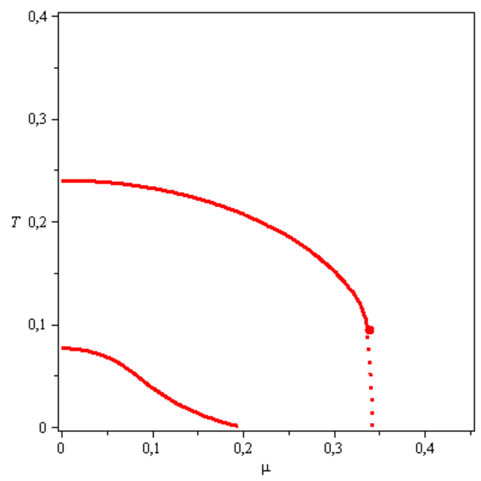
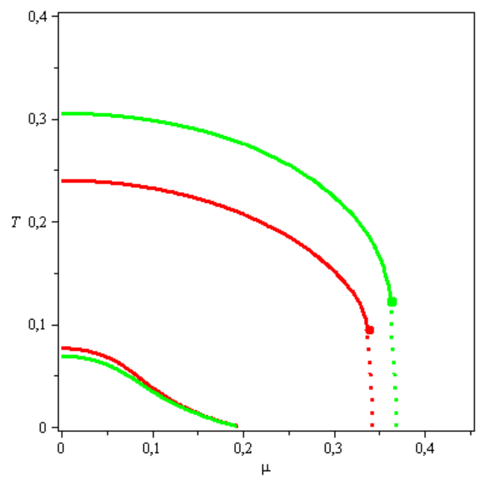
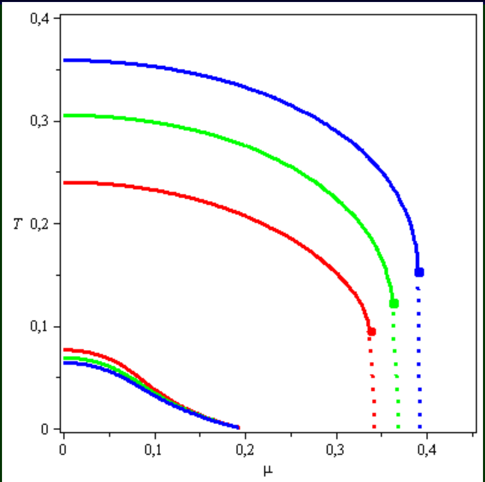

0,25
0,20
0,15
0,10
0,05
0
T
M
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
μ
M



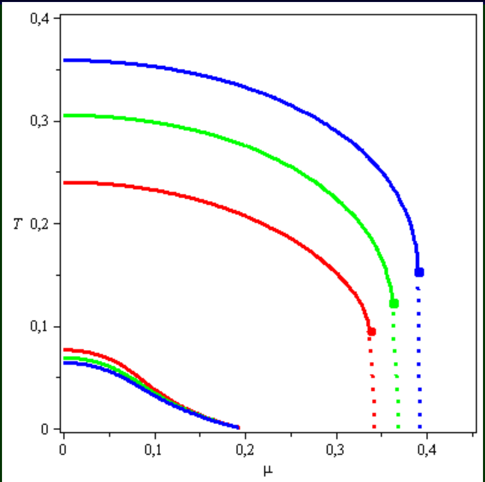
$\delta\mu = 0.3\Delta_0$; red: $eB_\perp = 0.5\Delta_0^2$;



$\delta\mu = 0.3\Delta_0$; red: $eB_\perp = 0.5\Delta_0^2$; green: $eB_\perp = 1.0\Delta_0^2$;



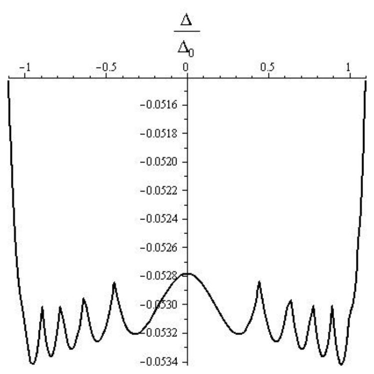
$\delta\mu = 0.3\Delta_0$; red: $eB_\perp = 0.5\Delta_0^2$; green: $eB_\perp = 1.0\Delta_0^2$; and blue: $eB_\perp = 1.5\Delta_0^2$



$\delta\mu = 0.3\Delta_0$; red: $eB_\perp = 0.5\Delta_0^2$; green: $eB_\perp = 1.0\Delta_0^2$; and blue: $eB_\perp = 1.5\Delta_0^2$

$B_\perp$ enlarges the symmetry broken phase (generic even for charged scalar field systems, Duarte, Farias, ROR, arXiv:1108.4428)

For the critical asymmetry case, $\delta\mu = \mu_c = \Delta_0$, $eB_\perp = 0.1\Delta_0^2$:



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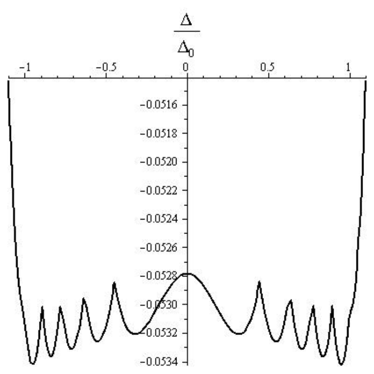

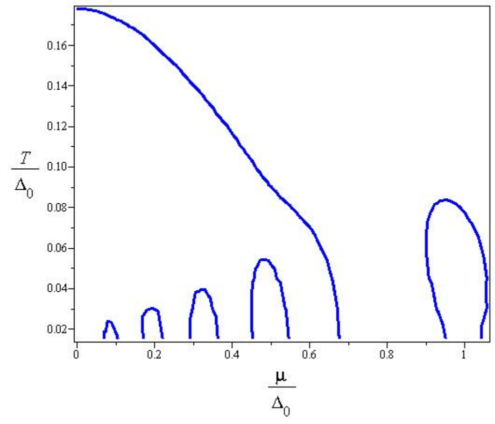

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  precise control of the gap in semiconductors devices:

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  precise control of the gap in semiconductors devices:
  $\Rightarrow$ use oblique magnetic fields at given doping (chemical potential) and temperature !