Correlated density and

Bernoulli potentials in superconductivity

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1. Nonlocal kinetic theory, correlated density
2. Bernoulli potential at superconductor surfaces - history
3. Measurements by Brown and Morris, charged vortices in HTSC probed by NMR
4. Bulk, surface charge, and surface dipole within Ginzburg-Landau theory - experimental suggestion
5. Conclusion, change of critical temperature due to bias, interaction with lattice deformation, vortex mass

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MPI for the Physics of Complex Systems

LPC/ISMRA

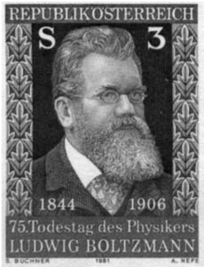
Michigan State University

Rostock University

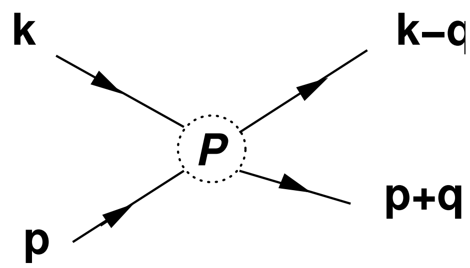
Ludwig Boltzmann

Born: 20 Feb 1844 Vienna, Austria
Died: 5 Oct 1906 Duino, Austria (Italy)





collision in collision out



Sitzungsberichte der Mathematisch-Naturwissenschaftlichen Classe der Kaiserlichen Akademie der Wissenschaften Abteilung IIa, Mathematik, Astronomie, Physik, Meteorologie und Technik, 10.10.1872:

$$\frac{\partial f(x,t)}{\partial t} = \int_0^\infty \int_0^{x+x'} \left[\frac{f(\xi,t)}{\sqrt{\xi}}\frac{f(x+x'-\xi,t)}{\sqrt{x+x'-\xi}} - \frac{f(x,t)}{\sqrt{x}}\frac{f(x',t)}{\sqrt{x'}}\right] \times \sqrt{xx'}\,\psi(x,x',\xi)\,dx'\,d\xi. \qquad 16)$$

Dies ist die Fundamentalgleichung für die Veränderung Function $f(x,t)$. Ich bemerke nochmal, dass die Wurzeln

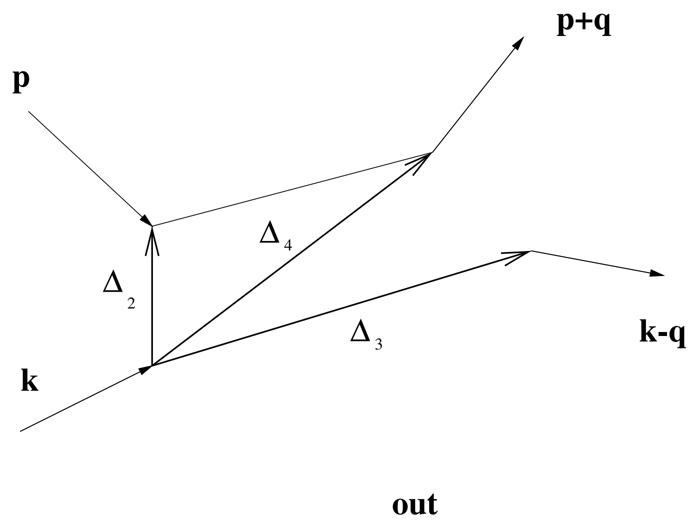
$$\frac{\partial f_k}{\partial t} = \sum_{pq} P\left(f_{k-q} f_{p+q} - f_k f_p\right)$$

instantaneous in time and local in space

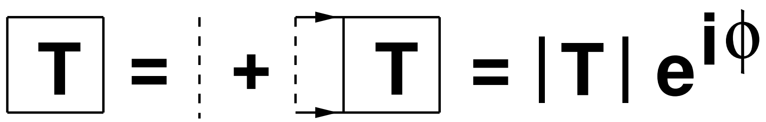
Non-local corrections necessary since virial corrections are missing (Enskog, Bogoliubov, Green, Ernst, Thirring..)

Nonlocal kinetic equation

$$\frac{\partial f_1}{\partial t}+\frac{\partial \varepsilon_1}{\partial k}\frac{\partial f_1}{\partial r}-\frac{\partial \varepsilon_1}{\partial r}\frac{\partial f_1}{\partial k}=\sum_{pq}\mathcal{P}\delta\left(\varepsilon_1+\varepsilon_2^- -\varepsilon_3^- -\varepsilon_4^- -2\Delta_E\right)\left[(1-f_1)(1-f_2^-)f_3^-f_4^- - f_1f_2^-(1-f_3^-)(1-f_4^-)\right]$$



with T-matrix



and shifts

$$\Delta_t = \left.\frac{\partial \phi}{\partial \Omega}\right|_{\varepsilon_1+\varepsilon_2} \qquad \Delta_2 = \left(\frac{\partial \phi}{\partial p}-\frac{\partial \phi}{\partial q}-\frac{\partial \phi}{\partial k}\right)_{\varepsilon_1+\varepsilon_2}$$

$$\Delta_E = -\left.\frac{1}{2}\frac{\partial \phi}{\partial t}\right|_{\varepsilon_1+\varepsilon_2} \qquad \Delta_3 = -\left.\frac{\partial \phi}{\partial k}\right|_{\varepsilon_1+\varepsilon_2}$$

$$\Delta_K = \left.\frac{1}{2}\frac{\partial \phi}{\partial r}\right|_{\varepsilon_1+\varepsilon_2} \qquad \Delta_4 = -\left(\frac{\partial \phi}{\partial k}+\frac{\partial \phi}{\partial q}\right)_{\varepsilon_1+\varepsilon_2}$$

where

$$\begin{aligned} f_1 &\equiv f(k,r,t)\\ f_2^- &\equiv f(p,r-\Delta_2,t)\\ f_3^- &\equiv f(k-q-\Delta_K,r-\Delta_3,t-\Delta_t)\\ f_4^- &\equiv f(p+q-\Delta_K,r-\Delta_4,t-\Delta_t)\end{aligned}$$

P. Lipavský, K. M., and V. Špička: *Kinetic equation for strongly interacting dense Fermi systems*
Annales de physique, 26,1 (2001) ISBN 2-86883-541-4

Summary of Correlated Observables

Quasiparticle parts (Landau theory – like)

$$n^{\rm qp} = \sum_k f \qquad \mathcal{Q}^{\rm qp} = \sum_k k\, f \qquad j^{\rm qp} = \sum_k \frac{\partial\varepsilon}{\partial k} f$$

$$\mathcal{E}^{\rm qp} = \sum_k \left(\frac{k^2}{2m} + \frac{1}{2}\Sigma_{mf}\right) f_k \qquad \mathcal{J}^{\rm qp}_{ij} = \sum_k \left(k_j \frac{\partial\varepsilon}{\partial k_i} + \delta_{ij}\varepsilon\right) f - \delta_{ij}\mathcal{E}^{\rm qp}$$

Two-particle correlated parts

$$n^{\rm mol} = \int d\mathcal{P}\, \Delta_t \qquad j^{\rm mol} = \int d\mathcal{P}\, \Delta_3$$

$$\mathcal{Q}^{\rm mol} = \int d\mathcal{P}\, \frac{k+p}{2}\, \Delta_t \qquad \mathcal{E}^{\rm mol} = \int d\mathcal{P}\, \frac{\epsilon_k+\epsilon_p}{2}\, \Delta_t$$

$$\mathcal{J}^{\rm mol}_{ij} = \frac{1}{2}\int d\mathcal{P}\, \left\{k_j\Delta_{3i} + p_j(\Delta_{4i} - \Delta_{2i}) + q_j(\Delta_{4i} - \Delta_{3i})\right\}$$

Conservation laws

$$\frac{\partial(n^{\rm qp} + n^{\rm mol})}{\partial t} + \frac{\partial(j^{\rm qp} + j^{\rm mol})}{\partial r} = 0$$

$$\frac{\partial(\mathcal{Q}^{\rm qp}_j + \mathcal{Q}^{\rm mol}_j)}{\partial t} + \sum_i \frac{\partial(\mathcal{J}^{\rm qp}_{ij} + \mathcal{J}^{\rm mol}_{ij})}{\partial r_i} = 0$$

$$\frac{\partial\mathcal{E}}{\partial t} = \frac{\partial(\mathcal{E}^{\rm qp} + \mathcal{E}^{\rm mol})}{\partial t} = 0$$

Internal energy- and momentum–gain $\mathcal{I}_{\rm gain} = \int d\mathcal{P} \Delta_E \qquad \mathcal{F}^{\rm gain} = \int d\mathcal{P} \Delta_K$

Two concepts of quasiparticles

Landau theory

number of particles = number of quasiparticles

$$n = \int \frac{dk}{(2\pi)^3} \tilde{f}_k$$

Quasiparticle energy

$$\tilde{\epsilon}_k = \frac{\delta \mathcal{E}}{\delta \tilde{f}_k}$$

Beth-Uhlenbeck equation of state '37

number of particles = number of free + bound particles

$$n = n_f + 2 n_f^2 B(n, T)$$

correspond to spectral concept

Quasiparticle energy as pole $\varepsilon = \frac{k^2}{2m} + \Sigma(k, \varepsilon)$

$$A = \frac{\Gamma}{(\omega - \frac{k^2}{2m} - \Sigma)^2 + \frac{1}{4}\Gamma^2} \approx \left(1 + \frac{\partial \Sigma}{\partial \omega}\right) 2\pi \delta(\omega - \varepsilon) + \frac{\wp'}{\omega - \varepsilon} \Gamma$$

In extended quasiparticle picture $n = \int \frac{d\omega}{2\pi} A\, f_{\rm FD} = \int \frac{dk}{(2\pi)^3} f_k + \int d\mathcal{P} \Delta_t$

total density = quasiparticle density + correlated density

- Coincides with balance from nonlocal kinetic equation $\rightarrow$ consistency
- Explicit calculation of Wigner function not necessary, correlated observables directly from quasiparticle kinetic equation

Relation to Landau theory

Landau theory works only if collisions $\tilde{I}$ treated instant and local: from kinetic equation $\frac{\partial \tilde{f}_k}{\partial t} = \tilde{I}_k$ follows:

number of particles

$$\frac{dn}{dt} = \int \frac{dk}{(2\pi)^3} \frac{\partial \tilde{f}_k}{\partial t} = \int \frac{dk}{(2\pi)^3} \tilde{I}_k \equiv 0$$

energy balance

$$\frac{d\mathcal{E}}{dt} = \int \frac{dk}{(2\pi)^3} \frac{\delta \mathcal{E}}{\delta \tilde{f}_k} \frac{\partial \tilde{f}_k}{\partial t} = \int \frac{dk}{(2\pi)^3} \tilde{\epsilon}_k \tilde{I}_k \equiv 0$$

Nonlocal kinetic theory

$$\frac{dn}{dt} = \frac{d}{dt} \int \frac{dk}{(2\pi)^3} f_k + \frac{d}{dt} \int d\mathcal{P} \Delta_t$$

$$\frac{d\mathcal{E}}{dt} = \int \frac{dk}{(2\pi)^3} \varepsilon_k \frac{\partial f_k}{\partial t} + \frac{d}{dt} \int d\mathcal{P} \frac{\varepsilon_k + \varepsilon_p}{2} \Delta_t - \int d\mathcal{P} \Delta_E$$

Instant approximation, last term can be rewritten $\Delta_E = -\frac{1}{2} \frac{\partial \phi}{\partial t}$

$$-\int d\mathcal{P} \Delta_E = \frac{1}{2} \int d\mathcal{P} \frac{\partial \phi}{\partial t} = \int \frac{dk}{(2\pi)^3} \int d\mathcal{P} \frac{\delta \phi}{\delta \tilde{f}_k} \frac{\partial \tilde{f}_k}{\partial t} \equiv \int \frac{dk}{(2\pi)^3} \epsilon^{\Delta} \frac{\partial \tilde{f}_k}{\partial t}$$

with rearrangement energy follows variational expression of Landau theory $\tilde{\varepsilon}_k = \varepsilon_k + \epsilon_k^{\Delta}$

Landau theory mimes for energy gain, but no correlated density !

Consequences of correlated density

Luttinger theorem: Fermi liquids in ground state should have no correlated matter, but

- Many systems turns not to ideal Fermi liquid at low temperatures
- Electrons in metals and nucleons develop coherent state – superconductivity
- There is a small fraction of correlated density in superconducting state
- Correlated density shifts Fermi momentum, i.e., shifts chemical potential μ
- Since electrochemical potential $\mu + e\varphi$=const, follows electrostatic potential

Calculate normal density from density of states h

$$n_n = 2\sum_p \Theta(\bar{\mu} - \epsilon_p) \approx n_0 - (e\varphi + \frac{m}{2}v^2)\frac{h(\mu)}{2\pi}$$

From the two-pole structure of the spectral function one finds the correlated density [$\omega_{\rm D}$ Debye frequency]

$$n_{\rm corr} \approx \frac{\partial h}{\partial \mu}\frac{\Delta^2}{4\pi}\ln\left(\frac{2\omega_D}{\sqrt{\rm e}\Delta}\right)$$

System stays neutral, $n = n_0$, therefore the two contributions cancel

$\longrightarrow$ follows electrostatic potential of Bernoulli type

$$e\varphi = -\frac{1}{2}mv^2 + \frac{\partial \ln h}{\partial \mu}\frac{\Delta^2}{2}\ln\left(\frac{2\omega_D}{\sqrt{\rm e}\Delta}\right)$$

- Shift of chemical potential causes internal electric fields
- Bernoulli potential currently best argument for our nonlocal kinetic theory

History of Bernoulli potential in sc - Theory

Equation of motion for condensate, London condition $m\mathbf{v} = -e\mathbf{A}$

$$m\dot{\mathbf{v}} = -e\frac{\partial \mathbf{A}}{\partial t} - e(\mathbf{v}\nabla)\mathbf{A} = e(\mathbf{E} + \mathbf{v}\times\mathbf{B}) + \nabla\left(e\varphi + \frac{1}{2}mv^2\right)$$

$$\nabla e\varphi = \mathbf{F}_s - \nabla\frac{1}{2}mv^2$$

Compare with Newton equation of motion $m\dot{\mathbf{v}} = e(\mathbf{E} + \mathbf{v}\times\mathbf{B}) + \mathbf{F}_s$

Hydrodynamics of charged ideal gas

F. Bopp, Z. f. Phys. 107 (1937) 623, F. London, *Superfluids* (1950)

V. S. Sorokin, JETP 19 (1949) 553 free energy responsible for sc contributes

$$e\varphi = -\frac{1}{2}mv^2$$

Quasiparticle Screening:

Force resulting from interaction between electrons and condensate acting on electrons to keep them at rest $\mathbf{F}_n + e\mathbf{E} = 0$

A.G. van Vijfeijken and F. S. Staas, Phys. Lett. 12 (1964) 175

Interaction between superfluid and normal electrons (fountain effect) reduces Bernoulli potential

$$\begin{aligned} \mathbf{F}_n &= e\nabla\varphi \\ n_n\mathbf{F}_n + n_s\mathbf{F}_s &= 0 \\ \mathbf{F}_s &= -\frac{n_n}{n_s}e\nabla\varphi \end{aligned}$$

$$e\varphi = -\frac{n_s}{n}\frac{1}{2}mv^2$$

Thermodynamic correction:

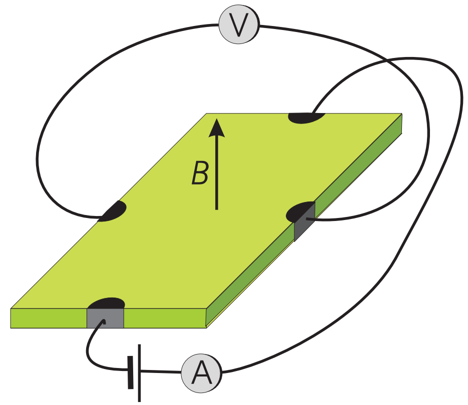
Condensate kinetic energy $f_{kin} = n_s\frac{1}{2}mv^2$ determines chemical potential

G. Ryckaizen, J. Phys. C 2 (1969) 1334

$$\begin{aligned} e\varphi &= -\mu = -\frac{\partial}{\partial n}f_{kin} \\ &= -\frac{n_s}{n}\frac{1}{2}mv^2 + 4\frac{n_n}{n}\frac{\partial \ln T_c}{\partial \ln n}\frac{1}{2}mv^2 \end{aligned}$$

Thermodynamic corrections strong close to T_c: Idea to measure material parameters

History of Bernoulli potential in sc - Experiment

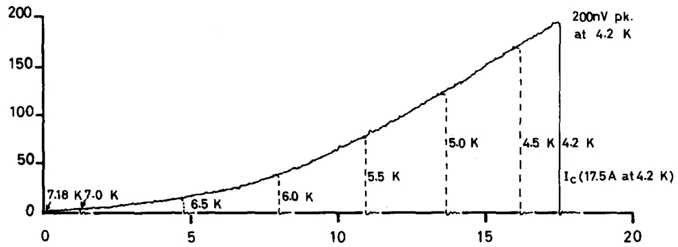


Ohmic contacts: *Null results* due to constant electrochemical potential

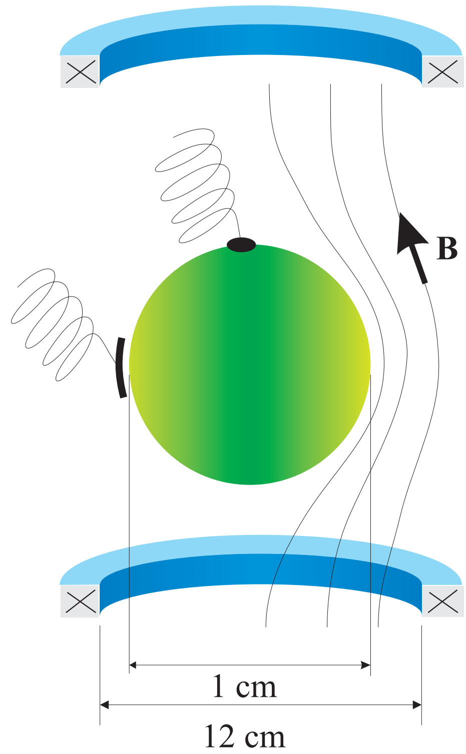
H. W. Levis, Phys. Rev 92 (1953) 1149, T. K. Hunt, Phys. Lett. 22 (1966) 42

Capacitive coupling: *No thermodynamic corrections* observed !

J. Bok, J. Klein, PRL 20 (1968) 660; T. D. Morris, J. B. Brown, Physica 55 (1971) 760



$$e\varphi = -\frac{n_s}{n}\frac{1}{2}mv^2 = -\frac{1}{n}\frac{B^2}{2\mu_0}$$



It should be $\delta f = \frac{1}{2}n_s m v^2$ and (BCS for Pb at $T = 7$K)

$$e\varphi = -\frac{\partial}{\partial n}\delta f = -\left(\frac{n_s}{n} - 4\frac{n_n}{n}\frac{\partial \ln T_c}{\partial \ln n}\right)\frac{m}{2}v^2 = -\left(0.1 + 3.2\right)\frac{m}{2}v^2$$

Why no signal of thermodynamic corrections?

Budd-Vannimenus theorem for superconductors

Modification of Budd-Vannimenus theorem (PRL 31 (1973) 1218)

$$e\left(\varphi_{\rm surf}-\varphi\right) \;=\; = n\frac{\partial}{\partial n}\left(\frac{f_{\rm el}}{n}\right)$$

Potential step at surface due to surface dipole in terms of free energy with no regards of potential inside

Answer (after 30 years) due to surface dipoles: Budd-Vannimenus theorem

with $\underline{e\varphi = -\frac{\partial}{\partial n} f_{\rm el}}$ and $f_{\rm el} = n_s \frac{1}{2} m v^2$

$$e\varphi_{\rm surf} = e\varphi + n\frac{\partial}{\partial n}\left(\frac{f_{\rm el}}{n}\right) = \underline{e\varphi + \frac{\partial}{\partial n} f_{\rm el}} - \frac{f_{\rm el}}{n} = -\frac{n_s}{n}\frac{1}{2}mv^2$$

Surface dipole compensates thermodynamic corrections exactly for homogeneous sc
P. Lipavský and J. Koláček and J.J. Mareš, K. Morawetz, PRB 65 (2002) 2507

Hope: inhomogeneous superconductors, vortices

Extended Ginzburg-Landau approach

Free energy $f[\psi, \mathbf{A}, n_n] = f_s + f_{\rm kin} + f_{\rm Coul} + f_{\rm mag}$

Condensation energy Gorter and Casimir
(Phys. Z. 35 (1934) 963)

$$f_s = U - \varepsilon_{\rm con}\varpi - \frac{1}{2}\gamma T^2\sqrt{1-\varpi}$$

Equilibrium $\partial f_s/\partial\varpi = 0$, at critical T_c is $\varpi = 0$

$$\varepsilon_{\rm con} = \frac{\gamma T^2}{4\sqrt{1-\varpi}} \quad \leftarrow \quad \varepsilon_{\rm con} = \frac{1}{4}\gamma T_c^2 \quad \text{and}$$

order parameter $\varpi = 1 - \frac{T^4}{T_c^4} \approx \frac{n_s}{n_s + n_n}$

Kinetic energy

Ginzburg and Landau proposed wave function
JETP 20 (1950) 1064

$$f_{\rm kin} = \frac{1}{2m^*}\left|\left(-i\hbar\nabla - e^*\mathbf{A}\right)\psi\right|^2$$

$$|\psi|^2 = \frac{n_s}{2} \quad \rightarrow \quad \varpi = \frac{2|\psi|^2}{n} = \frac{2|\psi|^2}{2|\psi|^2 + n_n}$$

1. Variation with respect to $\bar{\Psi}$: GL-equation
Effective potential (Bardeen Phys. Rev. 94 (1954) 554)

$$\frac{1}{2m^*}(-i\hbar\nabla - e^*\mathbf{A})^2\psi + \chi\psi = 0$$

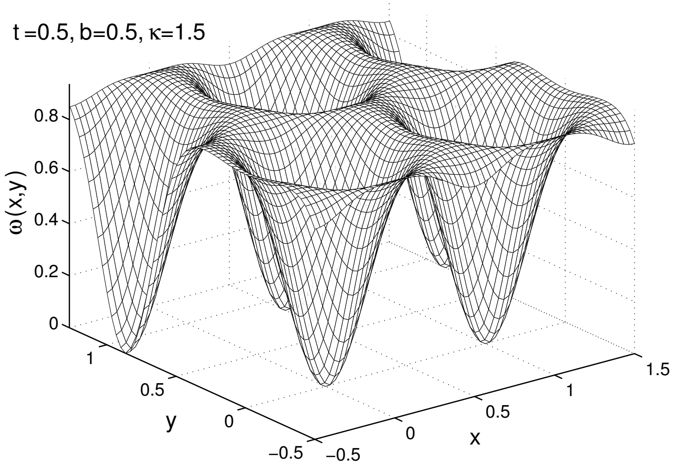
extends GL towards lower temperatures
Close to T_c: $\chi \to \alpha + \beta|\psi|^2$

$$\chi = -2\frac{\varepsilon_{\rm con}}{n} + \frac{\gamma T^2}{2n}\frac{1}{\sqrt{1 - \frac{2|\psi|^2}{n}}}$$

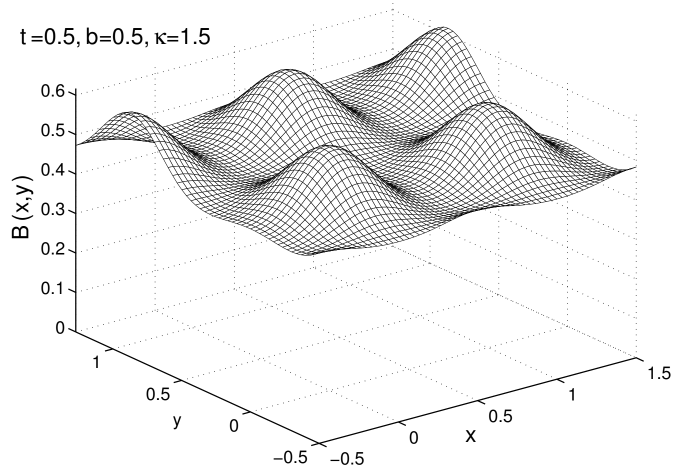
Abrikosov vortex lattices at temperatures below T_c

Numerical solution of Ginzburg-Landau equation extended to low temperatures (Bardeen)

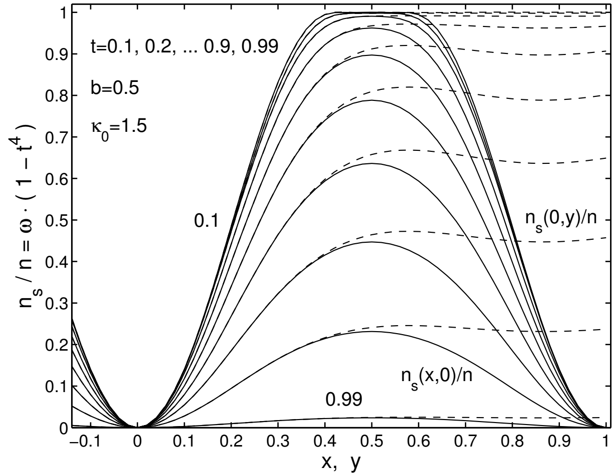
$$\frac{(-i\hbar\nabla - e^*\mathbf{A})^2}{2m^*}\psi - \frac{\gamma T_c^2}{2n}\left(1 - \frac{t^2}{\sqrt{1-\frac{2}{n}|\psi|^2}}\right)\psi = 0$$



Condensate density



Magnetic field



Profiles of the condensate density $n(x,y)$ at various temperatures

reduced temperature $T/T_c = 0.5$, mean magnetic field $\bar{B}/B_{c2} = 0.5$, GL parameter $\kappa_0 = 1.5$

- n_s smaller at boarders than nonmagnetic value $\longrightarrow$ nonlocal effects
- B higher than applied field in core $\longrightarrow$ sc compresses magnetic field in vortices

P. Lipavský, J. Koláček, K. Morawetz, E. H. Brandt, PRB 65 (2001) 144511

Surface potential within the Ginzburg-Landau theory

Bardeen's low temperature extension of GL
(free energy by Gorter Casimir two-fluid, subtraction of free energy of normal state)

$$f_{\rm el} \;=\; \frac{1}{2}\gamma T^2 + \frac{1}{2m^*}\bar{\psi}\left(-i\hbar\nabla - e^*\mathbf{A}\right)^2\psi - \varepsilon_{\rm con}\frac{2|\psi|^2}{n} - \frac{1}{2}\gamma T^2\sqrt{1-\frac{2|\psi|^2}{n}}$$

- Near T_c $\chi \approx \alpha + \beta|\psi|^2$ follows surface potential (Budd-Vannimenus)

$$e\phi_0 = \tfrac{1}{2n}\beta|\psi|^4$$

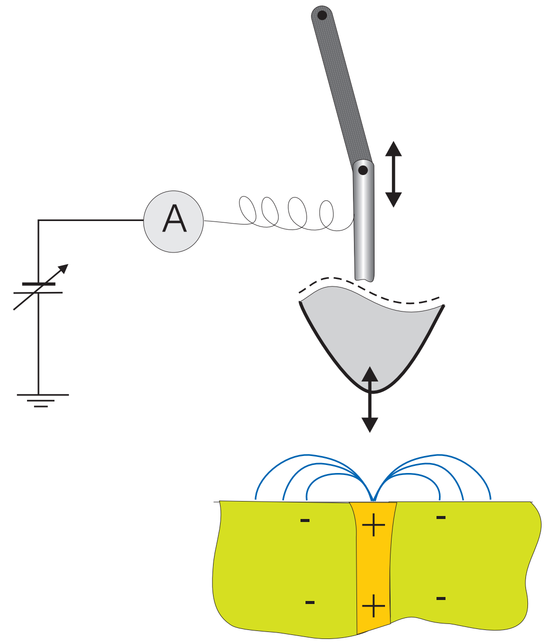
- Without surface dipole, surface potential equals to internal potential

$$e\phi = -\tfrac{1}{2m^* n}\bar{\psi}\left(-i\hbar\nabla - e^*\mathbf{A}\right)^2\psi + \frac{\partial\varepsilon_{\rm con}}{\partial n}\frac{2|\psi|^2}{n} - \frac{T^2}{2}\frac{\partial\gamma}{\partial n}\left(\frac{|\psi|^2}{n} + \frac{|\psi|^4}{2n^2}\right)$$

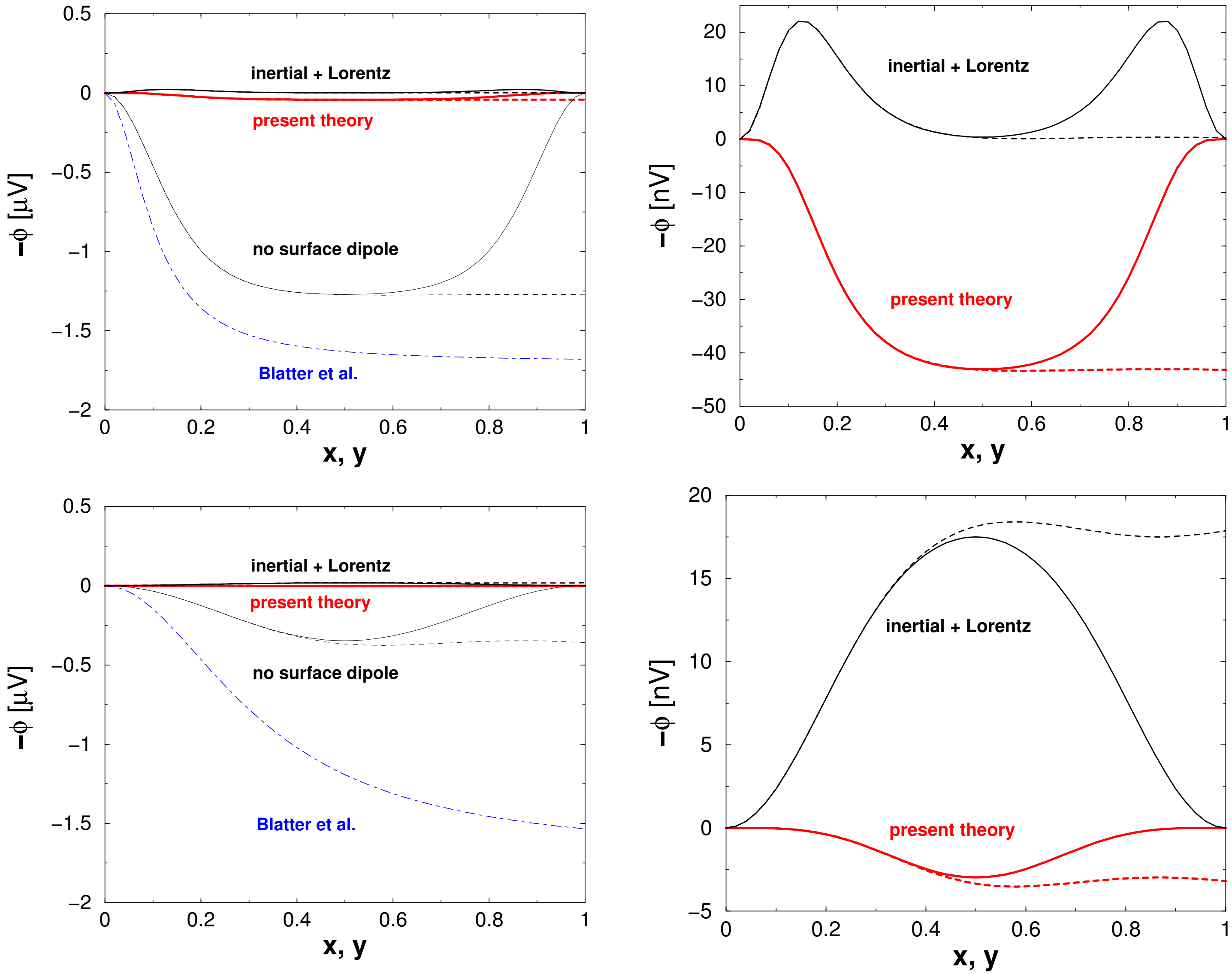
- Inertial and Lorentz forces: neglecting pairing forces

- Khomskii and Kusmartsev approximation adopted by Blatter:

$$e\phi_{\rm Bl} = \frac{\gamma T_c}{n}\frac{\partial T_c}{\partial n}|\psi|^2$$



Effect of surface dipole



Niobium

$\frac{T}{T_c} = 0.95,\ \kappa = 1.5,$

$\frac{B}{B_{c2}} = 0.7818$

$\frac{T}{T_c} = 0.95,\ \kappa = 0.78,$

$\frac{B}{B_{c2}} = 0.7818$

- internal potential and Blatter's result are similar (Clem model, neglect of $\frac{\partial \gamma}{\partial n}$)
- full theory and inertial/Lorentz forces are much smaller
- surface dipole cancels major part of pairing forces
- full theory and inertial/Lorentz forces result in different profiles and sign

1. Summary: Electrostatic potential

- Electrostatic potential above surface of thin superconducting layer with Abrikosov vortex lattice calculated
- Surface dipole strongly modifies magnitude of potential, in particular when GL wave function has a small magnitude due to $\phi_0 \propto |\psi|^4$, while without dipole $\phi_{\rm Bl} \propto |\psi|^2$
- Possible cases for which presented theory can be tested:
  - at vortex core $|\psi|^2 \propto r^2$ so that $\phi_0 \propto r^4$ while $\phi_{\rm Bl} \propto r^2$
    B close to B_{c2} for thin layer
  - $$\langle\omega\rangle = \frac{(1-b)}{\beta_{\rm A}}, \ \langle\omega^2\rangle = \frac{(1-b)^2}{\beta_{\rm A}}$$
    with $\omega = \frac{|\psi|^2}{|\psi_\infty|^2}$, $b = \frac{B}{B_{c2}}$

    mean value becomes

$$\langle e\phi_0\rangle = \frac{\varepsilon_{\rm con}}{n\beta_{\rm A}} \left(1-t^2\right)^2 (1-b)^2$$

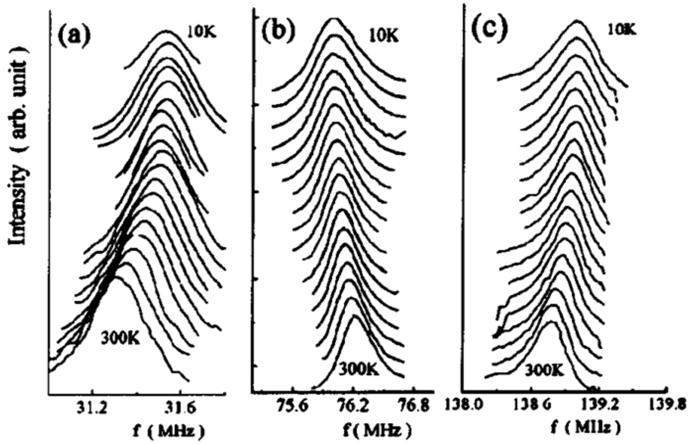
$$\langle e\phi_{\rm Bl}\rangle = \frac{\varepsilon_{\rm con}}{n\beta_{\rm A}} \frac{\partial \ln T_c}{\partial \ln n} 2\left(1-t^4\right)(1-b)$$

Charged vortices in HTSC probed by NMR

K. I. Kumagai, K. Nozaki and Y. Matsuda, PRB 63 (2001) 144502

- NMR frequency depends on B, $\gamma_{\rm Cu}$ and number N of holes per Cu/plane
- Polarization of Cu, coupling of spin with electrical field gradient leads to splitting of quadrupole resonance

$$\nu_Q^{NQR} = E_{\pm 3/2} - E_{\pm 1/2} = AN + C.$$



NQR | NMR lower satellite | NMR upper satellite

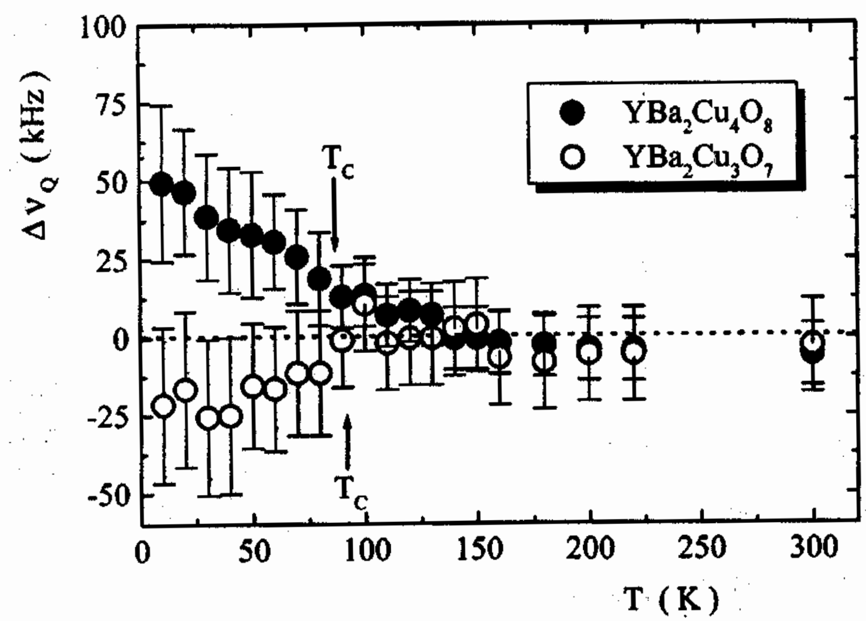


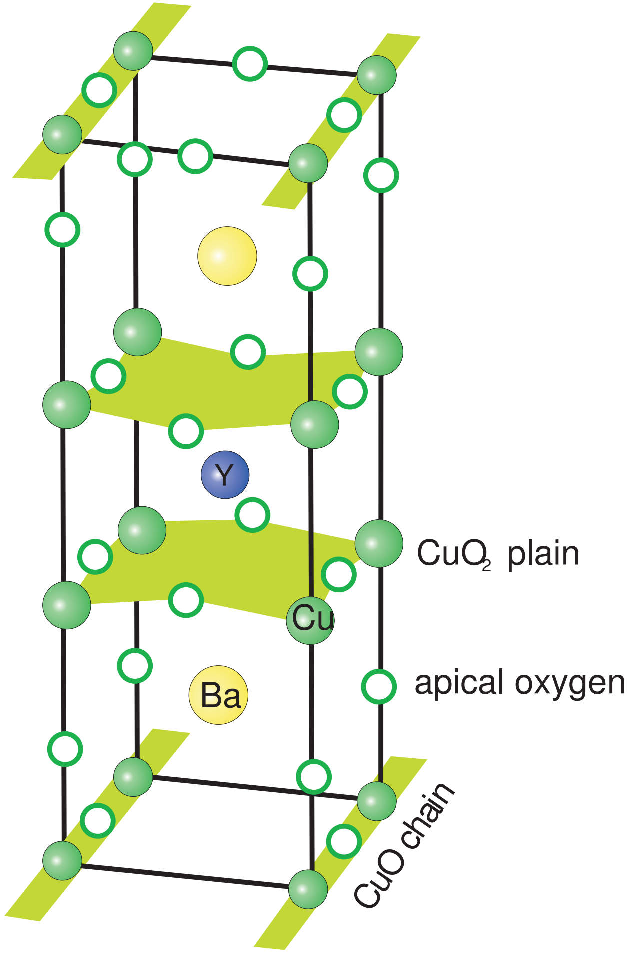
FIG. 7. T dependence of $\Delta\nu_Q = \nu_Q(0) - \nu_Q(H)$ for $YBa_2Cu_3O_7$ and $YBa_2Cu_4O_8$. In both materials nonzero $\Delta\nu_Q$ is clearly observed below T_c, showing that the electron density outside the core differs from that in zero field.

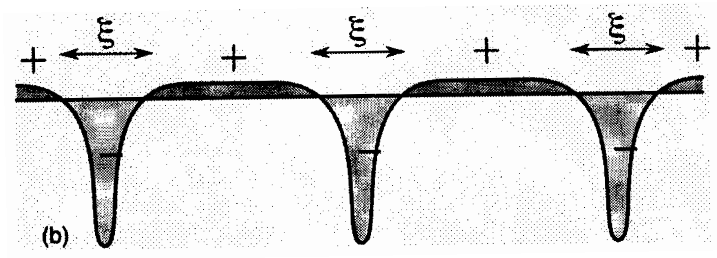
$$\begin{aligned}
\nu_1(B) &= E_{\frac{1}{2}} - E_{-\frac{1}{2}} = \gamma_{\rm Cu} B \\
\nu_2(B) &= E_{-\frac{1}{2}} - E_{-\frac{3}{2}} = \gamma_{\rm Cu} B - \nu_Q^{NQR} \\
\nu_3(B) &= E_{\frac{3}{2}} - E_{\frac{1}{2}} = \gamma_{\rm Cu} B + \nu_Q^{NQR}
\end{aligned}$$

Problems with NMR-lines in YBCO

- Charge accumulated in vortex core per layer (BCS) $Q \sim \frac{d \ln T_c}{d \ln \mu} \sim 10^{-5}e - 10^{-6}e$ exp : $10^{-2}e$
- Underdoped regime: $Q > 0$, overdoped: $Q < 0$, contrast to experiment

Structure $\mathrm{YBa_2Cu_3O_{6+x}}$





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Suggestion

- all lines similar width $\Gamma \approx 200$kHz $\gg \delta\nu \approx 20$kHz

$$F_i(\tilde{\nu}) = \frac{1}{\pi\Omega} \int d\mathbf{r} \frac{\Gamma}{(\tilde{\nu} - \tilde{\nu}_i(B(r), N(r)))^2 + \Gamma^2}$$

- Integral over volume Ω includes vortex cores

charge transfer between planes and chains

- Local shifts of NMR frequencies reflect triangular structure of Abrikosov lattice
- Space variation of shifts comparable to line width

Space variation of NMR lines

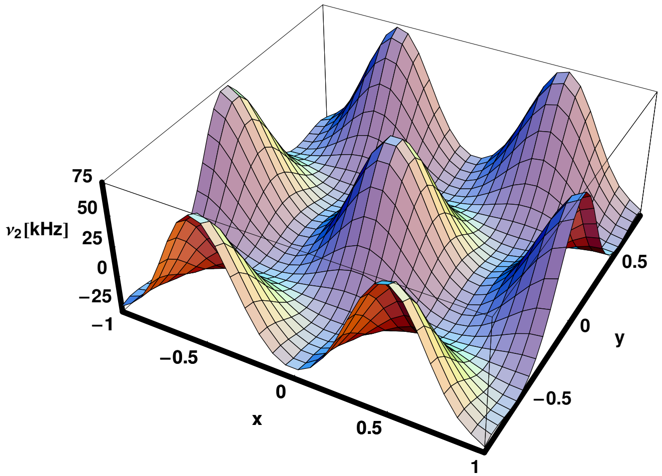
averaging of the NMR line over Abrikosov lattice

$$F_{2/3}(\tilde{\nu}) = \frac{1}{\pi\Omega}\int d\mathbf{r}\frac{\Gamma}{(\tilde{\nu}-\tilde{\nu}_{2/3}(\mathbf{r}))^2+\Gamma^2} \qquad \nu_{2/3}(\mathbf{r}) = \gamma B(\mathbf{r}) \mp C \mp AN(\mathbf{r})$$

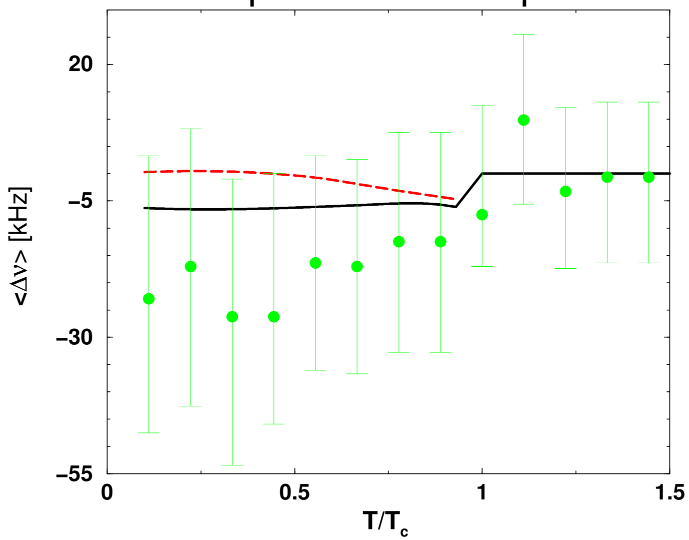
density $N(\mathbf{r}) = \frac{\Omega_{Cu}}{e}(\rho(\mathbf{r})-\rho_\infty)$, given by electrostatic potential via layered structure screening:

Lawrence/Doniach model : $\rho(\mathbf{k}) = \frac{2k\epsilon(1+\mathrm{e}^{-kD})}{(1-\mathrm{e}^{-2kD_{c-p}})(1+\mathrm{e}^{-kD_{p-p}})}\phi(\mathbf{k})$ compare 3D : $\rho(k) = -\epsilon k^2\phi(\mathbf{k})$

$B(\mathbf{r})$ and $\Psi(\mathbf{r})$ from extended GL-theory $\phi(\mathbf{r}) = \frac{|\Psi(\mathbf{r})|^2}{n^2}\gamma_{\mathrm{el}}T_c^2\frac{\partial\ln T_c}{\partial\ln n}$



Comparison with experiment



Shift $\langle\Delta\nu\rangle$ of $\Gamma = 140$kHz of a single crystal, and after averaging over grain orientation

- Space variation of shifts comparable to line width

$\longrightarrow$ no approximation by mean value

- Dominant role of magnetic field

2. Summary

Hall voltage measurements cannot be used - internal probes like NMR or capacitive pick-up are necessary

1. Bulk charge: Transfer of electrons from inner to outer regions of vortices creating Coulomb force to balance: (P. Lipavský, K. M., J. Koláček, J. J. Mareš, E. H. Brandt and M. Schreiber, PRB 69 (2004) 024524)
   - Electrons rotate around vortex center, inertial (centrifugal)
   - Magnetic field pushes electrons via the Lorentz force outward
   - Paired electrons lower free energy, unpaired electrons attracted towards condensate around core
2. Surface charge: Bernoulli potential by charge build up in surface region $\max[\xi/\sqrt{2}, \lambda/2]$ (P. Lipavský, K. M., J. Koláček, J. J. Mareš, E. H. Brandt and M. Schreiber, PRB 71 (2005) 024526-1-7)
   - Surface charge extends over a range $L = \min[\xi/\sqrt{2}, \lambda/2]$
   - Contrast to former theories: surface charge is not localized on Thomas-Fermi screening length $\lambda_{\rm TF}$
3. Bulk and surface charge can be measured: first observation of charge transfer with dominant contribution of pairing forces K. Kumagai, K. Nozaki, and Y. Matsuda PRB 63 (2001) 144502
   - Reproduced by assuming charge transfer between planes and chains

   P. Lipavský, J. Kolácek, K. Morawetz, E. H. Brandt, PRB 66 (2002) 134525
4. surface dipole: all contributions of pairing forces are canceled by surface dipole (Morris/Brown), P. Lipavský, K. M., J. Koláček, J. J. Mareš, E. H. Brandt and M. Schreiber, PRB 70 (2004) 104518
   - resulting observable surface potential $e\phi_0 = -f_{\rm el}/n$ (Budd-Vannimenus theorem generalized)

Conclusion

1. Bardeen's extension of GL theory provides simple description of electrostatic potentials (confirmed by BCS and DeGennes)

2. Bulk, surface charge measured by NMR, reproduced by extended GL theory

3. Surface dipole cancels pairing contribution to large extend

4. Suggestion to measure electrostatic potential above vortices to access thermodynamic corrections

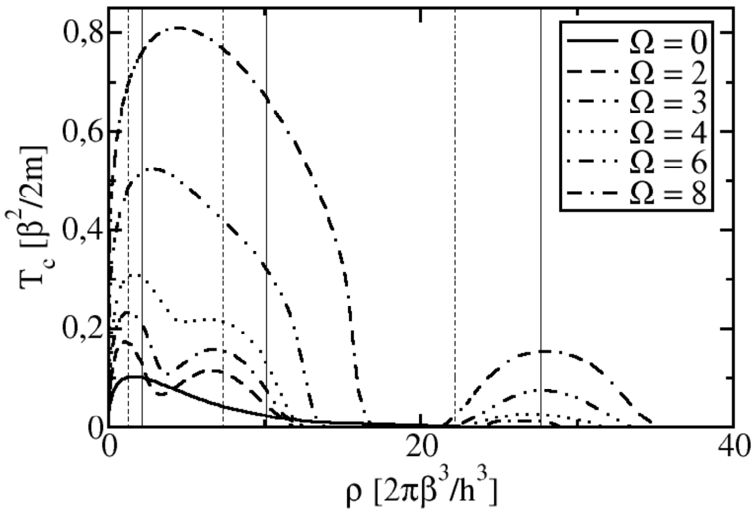
5. External electric field creates surface charges and critical temperature can be changed

$$\frac{L^2}{\xi^2(T^*)} = g\left(\frac{EL}{U}\right) \qquad \text{with } \sqrt{g}(x) \tan \sqrt{g}(x) = x$$

   P. Lipavský, K. Morawetz, J. Kolacek, T. J. Yang, PRB 73 (2006) 052505

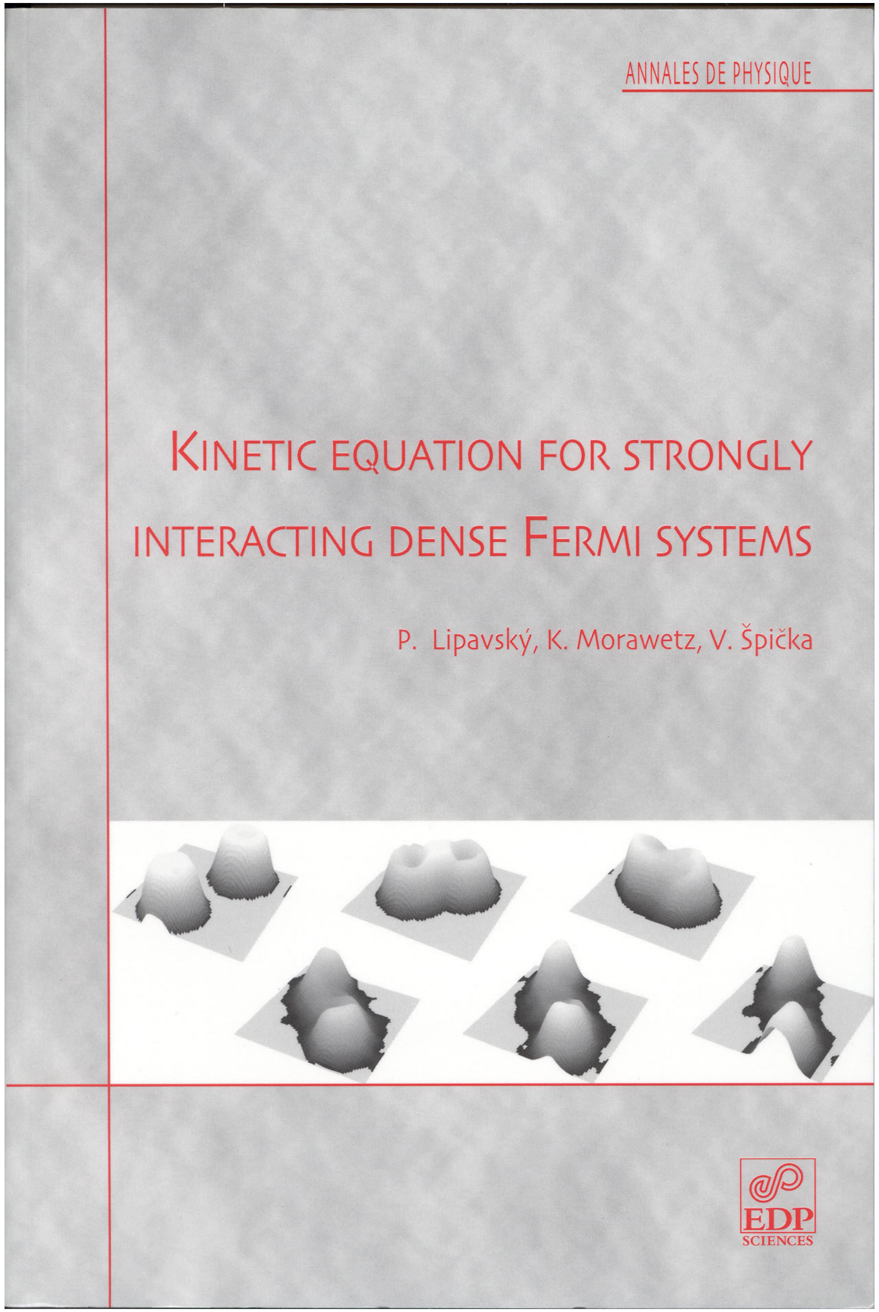
6. Change of critical temperature due to presence of cavity
   - oscillations of critical temperature T_c due to the cavity
   - second branch of Cooper-pairing for high densities
   - T_c enhanced for increasing opacity Ω

   K. Morawetz, M. Schreiber, B. Schmidt, P. Lipavský, PRB 72 (2005) 174504



7. Forces deforming lattice expressed as electrostatic forces, gradient corrections, effective mass

   P. Lipavský, K. Morawetz, J. Kolacek, T. J. Yang, PRB in press (2007), cond-mat/0609669



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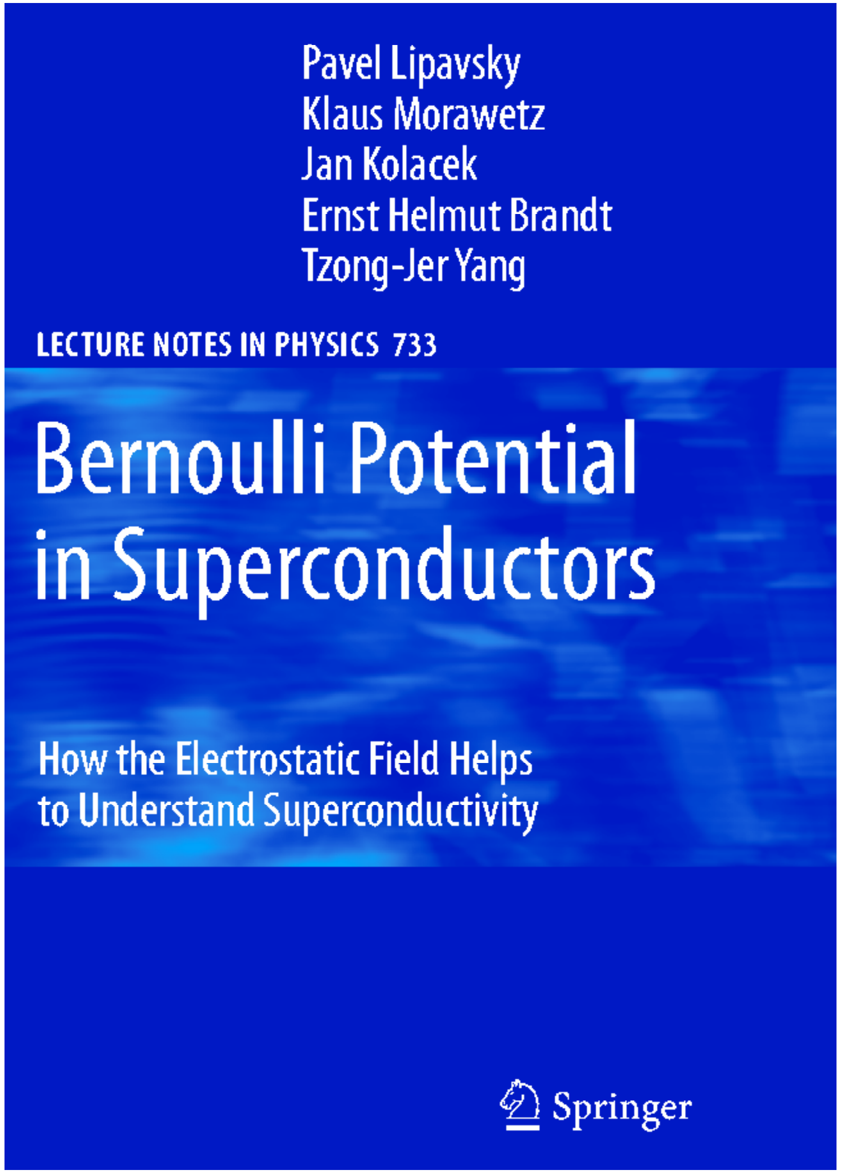

Lecture Notes in Physics, Springer (2007)