Enhancement of Tc due to charge transfer

Forschungszentrum Dresden Rossendorf

MAX-PLANCK-GESELLSCHAFT

K. Morawetz[1,2,3], P. Lipavský[4], J. Koláček[4], E. H. Brandt[5]

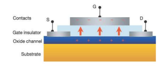
[1]Forschungszentrum Rossendorf, PF 51 01 19, 01314 Dresden, Germany
[2] International Center for Condensed Matter Physics (ICCMP), 70904-910, Brasília-DF, Brazil
[3]Max-Planck-Institute for the Physics of Complex Systems, Nöthnitzer Str. 38, 01187 Dresden, Germany
[4]Academy of Sciences, Cukrovarnická 10, 16200 Praha 6, Czech Republic
[5]Max-Planck-Institute for Metals Research, D-70506 Stuttgart, Germany

ICCMP CIFMC

Institute of Physics AS CR

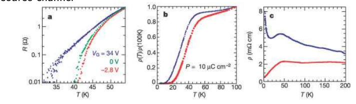
Experimental motivation

Long history: R. E. Glover and M. D. Sherrill, PRL 5 (1960) 248 ...



Electric field effect in correlated oxide systems C.H. Ahn, J.M. Triscone, J. Mannhart, Nature 424 (2003) 1015

Depletion and enhancement of carrier density, of the carrier density in drain-source channel



(a) $\approx$ 8-nm-thick $YBa_2Cu_3O_{7-\delta}$ channel with $\approx$ 300-nm-thick $Ba_{0.15}Sr_{0.85}TiO_3$ gate insulator (J. Mannhart, Supercond. Sci. Technol. 9 (1996) 49)

(b) $\approx$ 2-nm-thick $GdBa_2Cu_3O_{7-\delta}$ film induced by 300-nm-thick PZT layer (ferroelectric gate) normalized

(c) $\approx$2-nm-thick $GdBa_2Cu_3O_{7-\delta}$ film with doping level close to superconductor-insulator transition, induced by a 300-nm-thick PZT layer at 1 T (C. H. Ahn et al., Science 284 (1999) 1152)

Ginzburg Landau equation under external bias

$$\frac{1}{2m}(-i\hbar\nabla - e\mathbf{A})^2\Psi + \alpha\Psi + \beta|\Psi|^2\Psi = 0,$$

with the mass $m = 2m_e$ and charge $e = 2e_e$ of the Cooper pairs, de-Gennes surface conditions $\frac{\nabla\Psi}{\Psi}\big|_{x=0} = \frac{1}{b}$, $\frac{1}{b} = \frac{1}{b_0} + \frac{E}{\varphi_{\rm fe}}$, with the characteristic potential [P. Lipavsky, K. Morawetz, J. Kolacek, T. Yang, PRB 73, 052505]

$$\frac{1}{\varphi_{\rm fe}} = \frac{4e}{mc^2}\,\kappa^2\,\eta\,\frac{\partial \ln T_c}{\partial \ln n}$$

(few MeVs for conventional superconductors), Anderson theorem: only indirect influence of electric fields via boundary condition

Phase transition in thin layers under bias

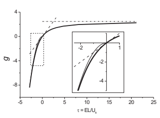
Electric field applied only at $x = 0$, while outer surface at $x = L$ is free, $\alpha^* = -\frac{\gamma T_c}{n}(T_c - T^*)$, boundary leads to $\frac{L}{\xi^*}\tan\frac{L}{\xi^*} = \frac{EL}{\varphi_{\rm fe}}$ with

$$\xi^* = \frac{\hbar}{\sqrt{-2m^*\alpha^*}} = \frac{\xi_{\rm GL}}{\sqrt{1-\frac{T^*}{T_c}}}$$

$$\sqrt{g}\,\tan\sqrt{g} = \tau$$

Transition temperature changes

$$T^* = T_c - T_c\frac{\xi^2_{\rm GL}}{L^2}g\left(\frac{EL}{\varphi_{\rm fe}}\right)$$
$$\approx T_c - \eta\frac{\partial T_c}{\partial n}\frac{\epsilon_0 E}{eL} + \mathcal{O}\left(\frac{EL}{\varphi_{\rm fe}}\right)$$



Transition temperature of thick layers $|EL| \gg |\varphi_{\rm fe}|$

$$T^* \approx T_c - T_c\frac{\xi^2_{\rm GL}}{L^2}g\left(\frac{EL}{\varphi_{\rm fe}}\right) \quad \lim_{\tau\to\infty} g(\tau) = \pi^2/4$$

Case A) Suppressive orientation of the electric field $EL/\varphi_{\rm fe} > 0$

$$T_c - T^* < T_c\frac{\pi^2\xi^2_{\rm GL}}{4L^2}.$$

Limited by layer thickness, value of E does not matter in asymptotic regime

Case B) Electric field reversed, supports superconductivity $g \to -\tau^2$

$$T^* \to T_c + T_c\frac{E^2\xi^2_{\rm GL}}{\varphi^2_{\rm fe}}$$

Question: T^* does not depend on width L ? Explanation:

- From boundary condition follows $L^2/\xi^{*2} = g \to -\tau^2 = -\frac{E^2L^2}{\varphi^2_{\rm fe}}$ and the coherence length is imaginary $\xi^* = i\frac{\varphi_{\rm fe}}{EL}$
- Accordingly, GL function exponentially decays from biased surface
- The stronger the field, the shorter the coherence length
- If $L \gg \xi^*$, GL wave function localised near biased surface, induced superconductivity not dependend on layer thickness

$\to$ Surface superconductivity

Where comes the field from ?

Idea: In layered superconductors the charge reservoir of chains allows a charge transfer to planes which creates huge local electric fields. This might be a mechanism responsible for high T_c. The electrostatic potential of Bernoulli type creates such fields.

History of Bernoulli potential in sc - Theory

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

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

Compare with Newton $m\dot{\mathbf{v}} = e(\mathbf{E}+\mathbf{v}\times\mathbf{B}) + \mathbf{F}_s$ $\quad \boxed{\nabla e\varphi = \mathbf{F}_s - \nabla\frac{1}{2}mv^2}$

Hydrodynamics of charged ideal gas

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

diamagnetic currents in SC are maintained by electrostatic potential $\quad e\varphi = -\frac{1}{2}mv^2$

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

Quasiparticle Screening:

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

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

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

Interaction between superfluid and normal electrons (fountain effect) reduces Bernoulli potential $\quad e\varphi = -\frac{n_s}{n}\frac{1}{2}mv^2$

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

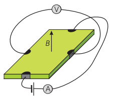
$$e\varphi = -\mu = -\frac{\partial}{\partial n}f_{kin} = \left(-\frac{n_s}{n} + 4\frac{n_n}{n}\frac{\partial\ln T_c}{\partial\ln n}\right)\frac{1}{2}mv^2$$

Thermodynamic corrections: Idea to measure material parameters

History of Bernoulli potential in sc - Experiment

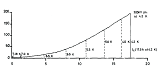
Ohmic contacts: *Null results* due to constant electro-chemical potential

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

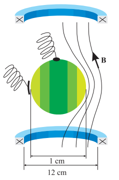


Capacitive coupling: *No thermodynamic corrections observed !*

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 $\delta f = \frac{1}{2}n_smv^2$ and (Pb at $T = 7$K)

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

Why no signal of thermodynamic corrections?

Budd-Vannimenus theorem for superconductors

Answer (after 30 years) due to surface dipoles: Modification of Budd-Vannimenus theorem $\quad e\varphi_{\rm surf} - e\varphi = n\frac{\partial}{\partial n}\left(\frac{f_{\rm el}}{n}\right)$

- Potential step at surface due to surface dipole in terms of free energy with no regards of potential inside
- With $e\varphi = -\frac{\partial}{\partial n}f_{\rm el}$ and $f_{\rm el} = n_s\frac{1}{2}mv^2$

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

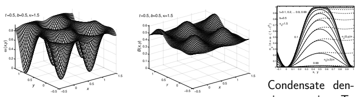
Surface dipole compensates thermodynamic corrections for homogeneous superconductors

P. Lipavský and J.J. Mareš, K. Morawetz, PRB 65 (2002) 2507

Hope: inhomogeneous superconductors, vortices

Abrikosov vortex lattices at temperatures below T_c

Ginzburg-Landau equation extended to low temperatures (Bardeen) $\quad \frac{(i\hbar\nabla + e^*\mathbf{A})^2}{2m^*}\psi - \frac{\gamma T_c^2}{2n}\left(1 - \frac{t^2}{\sqrt{1-\frac{2|\psi|^2}{n}}}\right)\psi = 0$



Condensate density $\quad$ Magnetic field $\quad$ Condensate density at various T

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

- n_s smaller at boarders than nonmagnetic value $\to$ nonlocal effects
- B higher than applied field in core $\to$ B compressed 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)

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

From GL equation $\frac{(-i\hbar\nabla - e^*\mathbf{A})^2}{2m^*}\psi = -\alpha\psi - \beta|\psi|^2\psi$ follows $f_{\rm el} = -\frac{1}{2}\beta|\psi|^4$ and surface potential reads (Budd-Vannimenus) $e\phi_0 = \frac{1}{2n}\beta|\psi|^4$, without surface dipole, surface potential equals to internal potential

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

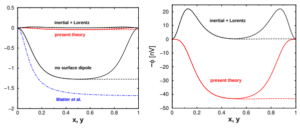
-Inertial and Lorentz forces: neglecting pairing forces

-Khomskii/Kusmartsev/Blatter approximation : $e\phi_{\rm Bl} = \frac{\gamma T_c}{n}\frac{\partial T_c}{\partial n}|\psi|^2$

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 $\quad$ mean value becomes
- $\langle\omega\rangle = \frac{(1-b)}{\beta_A}$, $\langle\omega^2\rangle = \frac{(1-b)^2}{\beta_A}$ $\quad \langle e\phi_0\rangle = \frac{\varepsilon_{\rm con}}{n\beta_A}\left(1-t^2\right)^2(1-b)^2$
  with $\omega = \frac{|\psi|^2}{|\psi_\infty|^2}$, $b = \frac{B}{B_{c2}}$ $\quad \langle e\phi_{\rm Bl}\rangle = \frac{\varepsilon_{\rm con}}{n\beta_A}\frac{\partial\ln T_c}{\partial\ln n}2\left(1-t^4\right)(1-b)$

Effect of surface dipole



Niobium

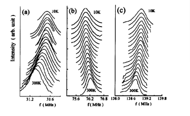
$$\frac{T}{T_c} = 0.95 \quad \kappa = 1.5 \quad \frac{B}{B_{c2}} = 0.7818$$

- internal potential and Blatter's result 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

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 $\nu_Q^{NQR} = E_{\pm3/2} - E_{\pm1/2} = AN + C$.



NQR $\quad$ NMR lower $\quad$ NMR upper satellite

$\nu_3(B) = E_{\frac{3}{2}} - E_{\frac{1}{2}} = \gamma_{\rm Cu}B + \nu_Q^{NQR}$

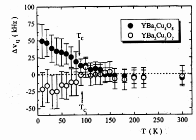


FIG. 7. T dependence of $\Delta\nu_Q = \nu_Q(0) - \nu_Q(H)$ for $YBa_2Cu_3O_7$ and $YBa_2Cu_4O_8$. In both materials nonzero $\Delta\nu_Q$ is clearly observed below T_c, showing that the electron density outside the core differs from that in zero field.

Problems:

- Charge in vortex core(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

Space variation of NMR lines

averaging of the NMR line over Abrikosov lattice

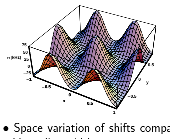
$$F_{2/3}(\bar\nu) = \frac{1}{\pi\Omega}\int d\mathbf{r}\frac{\Gamma}{(\bar\nu - \bar\nu_{2/3}(\mathbf{r}))^2 + \Gamma^2} \qquad \nu_{2/3}(\mathbf{r}) = \gamma B(\mathbf{r}) \mp C \mp AN(\mathbf{r})$$

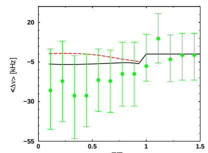
$N(\mathbf{r}) = \frac{\Omega_{\rm Cu}}{e}(\rho(\mathbf{r}) - \rho_\infty)$ by potential via layered structure screening (Lawrence/Doniach):

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

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

Comparison with experiment





- Space variation of shifts comparable to line width

$\to$ no approximation by mean value

P. Lipavský, J. Koláček, K. Morawetz, E. H. Brandt, PRB 66 (2002) 134525

$\Delta\nu$ ($\Gamma = 140$kHz) of single crystal and grain-orientation averaged

Advertisement: *Bernoulli potential in superconductors - how the electrostatic field helps to understand superconductivity*, P. Lipavský, J. Kolácek, K. Morawetz, E. H. Brandt, T. J. Yang
Lecture Notes in Physics 733, Springer, 2007