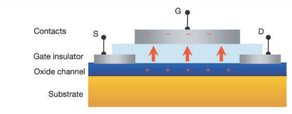
Surface superconductivity under field bias

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

[1]Münster University of Applied Science, Stegerwaldstrasse 39, 48565 Steinfurt, Germany
[2] International Institute of Physics (IIP), Universidade Federal do Rio grande do Norte
[3]Academy of Sciences, Cukrovarnická 10, 16200 Praha 6, Czech Republic
[4]Max-Planck-Institute for Metals Research, D-70506 Stuttgart, Germany

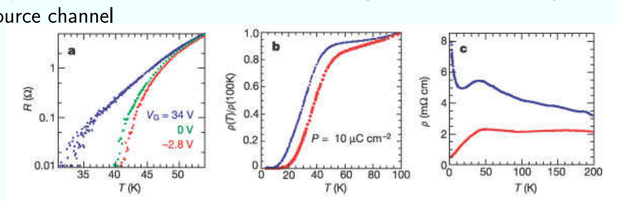
Experimental motivation

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) ≈ 8-nm-thick $YBa_2Cu_3O_{7-\delta}$ channel with ≈ 300-nm-thick $Ba_{0.15}Sr_{0.85}TiO_3$ gate insulator (J. Mannhart, Supercond. Sci. Technol. 9 (1996) 49)
(b) ≈ 2-nm-thick $GdBa_2Cu_3O_{7-\delta}$ film induced by 300-nm-thick PZT layer (ferroelectric gate) normalized
(c) ≈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

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

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

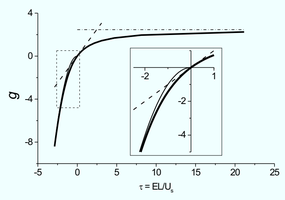
Electric field applied only at $x = 0$, while outer surface at $x = L$ is free, $\alpha^* = -\frac{\gamma T_c}{n}(T_c - T^*)$, boundary leads to $\frac{L}{\xi^*}\tan\frac{L}{\xi^*} = \frac{EL}{\varphi_{\rm fe}}$ with

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

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

Transition temperature changes

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



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

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

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

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

Limited by layer thickness, value of E does not matter in asymptotic regime
Case B) Electric field reversed, supports superconductivity $g \to -\tau^2$

$$T^* \to T_c + T_c\frac{E^2\xi_{\rm GL}^2}{\varphi_{\rm fe}^2}$$

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

- From boundary condition follows $L^2/\xi^{*2} = g \to -\tau^2 = -\frac{E^2L^2}{\varphi_{\rm fe}^2}$ 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

→ 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 $m\dot{\mathbf{v}} = e(\mathbf{E} + \mathbf{v}\times\mathbf{B}) + \mathbf{F}_s$

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

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

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

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

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

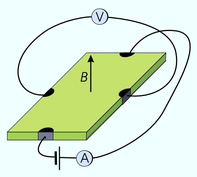
Thermodynamic correction:
Condensate kinetic energy $f_{kin} = n_s\frac{1}{2}mv^2$ determines chemical potential
G. Ryckaizen, J. Phys. C **2** (1969) 1334

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

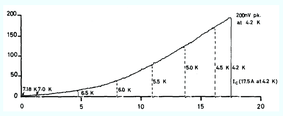
Thermodynamic corrections: Idea to measure material parameters

History of Bernoulli potential in sc - Experiment

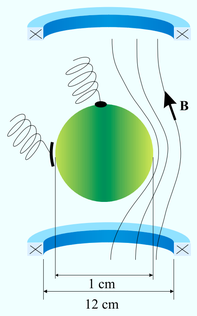
Ohmic contacts: *Null results* due to constant electrochemical potential
H. W. Levis, Phys. Rev 92 (1953) 1149, T. K. Hunt, Phys. Lett. 22 (1966) 42



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 $\delta f = \frac{1}{2}n_s mv^2$ 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

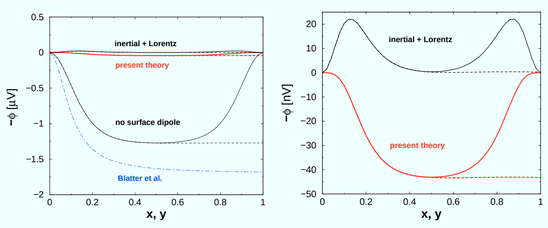
$$e\varphi_{\rm surf} - e\varphi = n\frac{\partial}{\partial n}\left(\frac{f_{\rm el}}{n}\right)$$

- 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. Koláček and J.J. Mareš, K. Morawetz, PRB 65 (2002) 2507
Hope: inhomogeneous superconductors, vortices

Effect of surface dipole



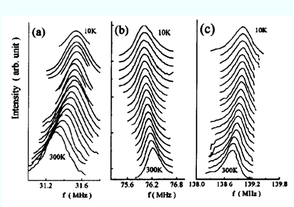
Niobium

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

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



NQR NMR lower NMR upper satellite

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

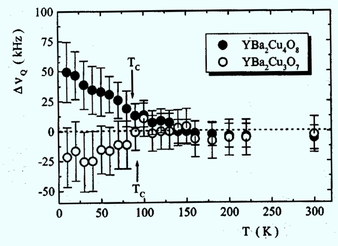


FIG. 7. T dependence of $\Delta\nu_Q = \nu_Q(0) - \nu_Q(H)$ for $YBa_2Cu_3O_7$ and $YBa_2Cu_4O_8$. In both materials nonzero $\Delta\nu_Q$ is clearly observed below T_c, showing that the electron density outside the core differs from that in zero field.

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

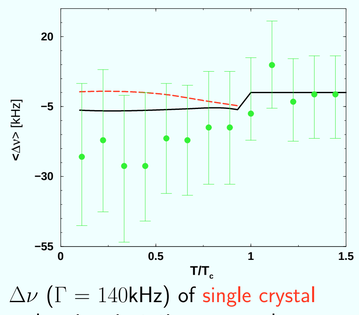
$$F_{2/3}(\tilde\nu) = \frac{1}{\pi\Omega}\int d\mathbf{r}\frac{\Gamma}{(\tilde\nu - \tilde\nu_{2/3}(\mathbf{r}))^2 + \Gamma^2} \qquad \nu_{2/3}(\mathbf{r}) = \gamma B(\mathbf{r}) \mp C \mp AN(\mathbf{r})$$

$N(\mathbf{r}) = \frac{\Omega_{Cu}}{e}(\rho(\mathbf{r}) - \rho_\infty)$ by potential via layered structure screening (Lawrence/Doniach):
$\rho(\mathbf{k}) = \frac{2k\epsilon(1+e^{-kD})}{(1-e^{-2kD_{c-p}})(1+e^{-kD_{p-p}})}\phi(\mathbf{k})$
compare 3D: $\rho(k) = -\epsilon k^2\phi(\mathbf{k})$

$B(\mathbf{r})$ and $\Psi(\mathbf{r})$ from extended GL-theory $\phi(\mathbf{r}) = \frac{|\Psi(\mathbf{r})|^2}{n^2}\gamma_{\rm el}T_c^2\frac{\partial\ln T_c}{\partial\ln n}$
- Space variation of shifts comparable to line width

→ no approximation by mean value
P. Lipavský, J. Koláček, K. Morawetz, E. H. Brandt, PRB 66 (2002) 134525

Comparison with experiment



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

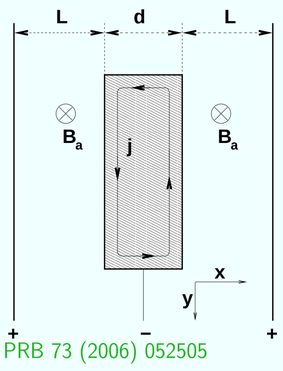
Effective magnetocapacitance

Aim: effective capacitance and surface critical field in dependence on applied voltage and magnetic field

- Total energy of capacitor with area S, $\frac{1}{2}\epsilon_0E^2LS + \sigma S$
- Capacitance $\frac{S}{C} = \frac{L}{\epsilon_0} + \frac{1}{\epsilon_0^2}\frac{\partial^2\sigma}{\partial E^2}$
- Ginzburg Landau equation with external bias $\frac{1}{2m}\left(-i\hbar\nabla - e\mathbf{A}\right)^2\Psi + \alpha\Psi + \beta|\Psi|^2\Psi = 0$ de-Gennes surface conditions

$$\frac{\nabla\Psi}{\Psi}\Big|_{x=0} = \frac{1}{b}, \qquad \frac{\nabla\Psi}{\Psi}\Big|_{x=d} = -\frac{1}{b},$$

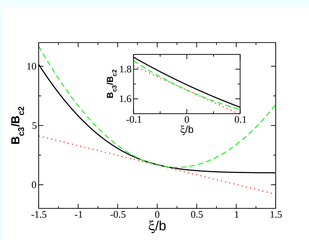
where extrapolation length $\frac{1}{b} = \frac{1}{b_0} + \frac{E}{\varphi_{\rm fe}}$,



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

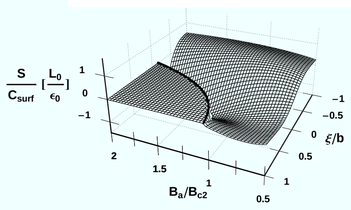
Nucleation of surface superconductivity

Nucleation possible if $-\alpha$ equals eigenvalue of linearized GL equation
- maximal nucleation temperature by maximal $\tilde\alpha = \max[\alpha]$
- corresponds to highest attainable critical magnetic field



Effective capacitance

$$\frac{S}{C_{\rm surf}}\Big|_0 = \frac{L_0}{\epsilon_0}\left(\frac{l}{\xi}\right)^{3.25} h\left(\frac{\xi}{b}\right)$$



	ϵ_c/n [μeV]	κ_0	n [10^{28}m^{-3}]	$\frac{\partial\ln T_c}{\partial\ln n}$	$\frac{\partial\ln\gamma}{\partial\ln n}$	$1/\varphi_{\rm el}$ 1/MV	L_0/ϵ_0 nm^2/pF	$C_s/C_n - 1$ S=10mm^2, l=0.1μm
Nb	4.585	0.78	2.2	0.74	0.42	4.52	0.248	10^{-9}
YBCO	750	55	0.5	-4.82	-4.13	-207.5	2547	10^{-4}

K. Morawetz, P. Lipavsky, J. Kolaček, E. H. Brandt, PRB 78 (2008) 054525,
K. Morawetz, P. Lipavsky, J. J. Mares, New J Phys., 11 (2009) 023032-1-8

Summary

1. Change of critical temperature due to external field calculated with the help of extended Ginzburg Landau theory, DeGennes boundary conditions
2. Electrostatic potential above surface of thin superconducting layer with vortex lattice calculated, NMR observation of charge transfer reproduced
3. Influence of external magnetic fields parallel and electric field perpendicular to surface: nonlinear dependence of surface critical magnetic field, effective capacitance has a jump near B_{c3} to be measured

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 2008
Surface superconductivity controlled by electric field, P. Lipavský, J. Kolácek, K. Morawetz in *Nanoscience and Engineering in Superconductivity*, Springer 2010