Transport of entropy in strong magnetic field
III. Nernst effect and superconductivity

Kamran Behnia

Ecole Supérieure de Physique et de Chimie Industrielles
III. The Nernst effect and superconductivity

A. Vortices as a source of Nernst effect

B. Superconducting fluctuations and the Nernst effect

C. Review of thermoelectricity of correlated superconductors
III A.
Mobile Vortices

Possible sources of the Nernst effect

• Quasi-particles (normal state)
• Vortices (mixed state)
• Gaussian fluctuations (short-lived Cooper pairs) (normal state)
• Phase fluctuations (short-lived vortices) (normal state)
Nernst effect in the vortex state

A superconducting vortex is:
- A quantum of magnetic flux
- An entropy reservoir
- A topological defect

- Thermal force on the vortex: $F = - S_\phi \nabla T$ ($S_\phi$: vortex entropy)
- The vortex moves
- The movement leads to a transverse voltage: $E_y = v_x B_z$
A superconductor

• **Perfect conductor**
  Resistivity is zero

• **Perfect diamagnet**
  The magnetic field is totally expelled

A macroscopic manifestation of quantum mechanics!

The superconducting order parameter is a wave–function:

\[ \Psi = \psi_0 e^{i\phi} \]

- amplitude
- phase
A superconducting vortex

- Superfluid density vanishes in the core of the vortex (coherence length $\xi$).
- Magnetic field penetrates inside the vortex (penetration depth $\lambda$).

In a type II superconductor $\lambda > \xi$.
A vortex is a quantum of magnetic flux

\[ \phi_0 = \frac{e}{2h} = 2 \times 10^{-15} \text{ Wb} \]

At a given field \( B \), the vortex density is \( B/\phi_0 \)
A vortex is an entropy reservoir

The vortex core is in the normal state. Since the entropy of the normal state exceeds the entropy of the superconducting state, the vortex has more entropy than the surrounding superfluid.
Thermal force

In presence of a thermal gradient and in absence of a charge current:

\[ F_{th} = -S_d \frac{\partial T}{\partial x} \]

\( S_d \) is the entropy carried by a moving vortex

Moving vortices generate an electric field.

Faraday law: \( E = -v_\phi \times B \)

\( V_\phi \) is the velocity of moving vortices.

Thermal force gives rise to the vortex Nernst effect!
**Lorentz force**

In presence of a charge current and a uniform temperature:

\[ F_L = J \times \phi_0 \] is the force on each vortex

Vortices move in the direction perpendicular to \( J \)

And generate an electric field: \( E = -v_\phi \times B \)

\( E \) is perpendicular to \( v_\phi \) and to \( B \).

Therefore \( E \parallel J \)

Lorentz force gives rise to flux flow resistivity
Nernst and Ettingshausen responses of vortices

Vortex movement

Nernst coefficient

\[ N = \frac{E_y}{-\nabla_x T} \]

Vortices are driven by a thermal force and generate a transverse voltage!

\[ \vec{B} \]

\[ \nabla T \]

\[ E_y \]
Nernst and Ettingshausen responses of vortices

Ettingshausen coefficient
\[ \varepsilon = \nabla_y T / J_e \]

Vortices are driven by a Lorentz force and generate a transverse temperature gradient (because they carry entropy!)
The entropies

Incremental entropy: $S_i$

Differential entropy: $S_d$

\[ S_i = -\phi_0 \frac{\partial^2 F}{\partial B \partial T} \]

Fig. 1. Theoretical vortex entropy at low fields, for a type II superconductor (reduced units).
Vortex differential entropy

\[ S_d = \frac{6\alpha \varphi_0 \gamma T}{\pi^2 H_{c2}(T)} \int_0^\beta dx \int_x^{\sqrt{x^2 + \beta^2}} y \text{sech}^2 y dy \]

Fig. 4. Transport entropy of niobium. The experimental points are from Ref. [33]. The solid curve is \( S_e \) (in reduced units) from equation (8) with \( \alpha = 1.35 \).
The entropy of an additional vortex

When the field exceeds $H_{c1}$, the lower critical field, a vortex enters!

When $H = H_{c1}$

\[ S \delta T + B \delta H = 0 \]  

(S is the entropy density)

Therefore:

\[ S = -B \frac{dH_{c1}}{dT} \]

The vortex density is:

\[ n = \frac{B}{\phi_0} \]

And entropy per length of each vortex:

\[ S_d = -\phi_0 \frac{\partial H_{c1}}{\partial T} \]
Flux flow resistivity

\[ E = \rho_{FF} J \]

\[ F_L = J \times \phi_0 = -\eta \nu_\phi \]

\[ E = -\nu_\phi \times B \]

\[ E = \frac{1}{\eta} (J \times \phi_0) \times B \]

\[ E_x = \frac{\phi_0}{\eta} BJ_x \quad \Rightarrow \quad \rho_{FF} = \frac{\phi_0}{\eta} B \]

\( \eta \) is the vortex viscosity
Flux flow Nernst effect

\[ N = \frac{E_y}{-\nabla_x T} \]

\[ F_{th} = -S_d \frac{\partial T}{\partial x} = -\eta v_\phi \]

\[ E = -v_\phi \times B \]

\[ E = \frac{1}{\eta} (-S_d \frac{\partial T}{\partial x}) \times B \]

\[ E_y = -\frac{S_d}{\eta} B \nabla_x T \]

\[ N = \frac{S_d}{\eta} B \]

\( \eta \) is the vortex viscosity
Combining resistivity and Nernst data to extract vortex entropy

Resistivity:
\[ \rho_{FF} = \frac{\phi_0}{\eta} B \]

Nernst:
\[ N = \frac{S_d}{\eta} B \]

\[ S_d = \phi_0 \frac{N}{\rho_{FF}} \]

In theory, simultaneous N and \( \rho_{FF} \) data allows one to extract \( S_d \)
Nernst effect in conventional superconductors

O. L. de Lange & F. A. Otter, JLTP 1975

Fig. 1. Sample geometry for measurement of the Ettingshausen and Nernst effects. \( ab = bc = 0.86 \text{ cm} \), \( AB = 3.9 \text{ cm} \), \( BC = 1.15 \text{ cm} \). Thickness is 0.12 cm. \( \Delta V_y = - \Delta V_{bd} \) is positive. \( \Delta V_x = \Delta V_{ac} \). The ends of the sample were clamped between copper blocks and current passed through leads connected to the blocks. The heaters were mounted in holes in these blocks.
Nernst effect in conventional superconductors

Fig. 2. Nernst voltage versus applied temperature gradient for Nb$_{80}$Mo$_{20}$ at $T = 3.26$ K.

O. L. de Lange & F. A. Otter, JLTP 1975
Nernst effect in conventional superconductors

Huebener 1967

A Nernst signal emerges in an immediate temperature range.

Fig. 1. Nernst voltage $U_N$ as function of magnetic field for different values of the temperature gradient. The temperature on top of each curve is the value on the hot end of the specimen. (a) 2.59 $\mu$m tin film; (b) 1.97 $\mu$m indium film.
Nernst effect in conventional superconductors

A Nernst signal emerges where vortices can move!

Huebener and Seher 1969
Nernst effect in conventional superconductors

A Nernst signal emerges where vortices can move!

Huebener and Seher 1969

Fig. 3. Influence of a longitudinal current of $I = 100$ mA on the voltage $U_{12}$. +: $8.0^\circ$K at heater, $I = 0$; ○: $8.0^\circ$K at heater, $I = 100$ mA; ×: $9.0^\circ$K at heater, $I = 0$; ●: $9.0^\circ$K at heater, $I = 100$ mA. (Specimen 5; temperature at heat sink = 4.2$^\circ$K.)
Transport Entropy of Vortex Motion in YBa$_2$Cu$_3$O$_7$

T. T. M. Palstra, B. Batlogg, L. F. Schneemeyer, and J. V. Waszczak

AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974

[Graphs and data showing transport properties of YBa$_2$Cu$_3$O$_7$.]

Ettingshausen effect in cuprates
Nernst effect in optimally-doped YBCO

A finite signal in the vortex liquid state!

(Ri, Huebener et al. 1994)

FIG. 3. Resistivity $\rho$ (a) and normalized Nernst electric field $E_y/\nabla_x T$ (b) versus temperature for an epitaxial, $c$-axis-oriented $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film at different magnetic fields applied parallel to the $c$ axis of the film.
Nernst effect in another cuprate superconductor

(Ri, Huebener et al. 1994)
In underdoped cuprates positive Nernst signal survives above $T_c$

Wang, Li and Ong, 2006

The fluctuating tail becomes longer in the underdoped regime
Nernst signal persists above $T_c$

$\text{Bi}_2\text{Sr}_2\text{CuO}_{6+\delta}$

$\rho (H=12\text{T})$

$\rho (H=0)$

$N(\text{H}=12\text{T})$

Capan et al., '02
Nernst signal persists above $H_{c2}$

FIG. 1: Left: Emergence of a field-induced “insulating” behavior in underdoped LSCO as revealed by temperature-dependence of resistivity. Right: The Nernst signal and $\tan \theta$ at 12T as a function of temperature for the same sample.

Capan et al., ‘04
Vortex–like excitations in the normal state of the underdoped cuprates?

Wang, Li and Ong, 2006

A finite Nernst signal in a wide temperature range above $T_c$
Preformed Cooper pairs in the pseudogap state?

Importance of phase fluctuations in superconductors with small superfluid density

V. J. Emery* & S. A. Kivelson†

* Department of Physics, Brookhaven National Laboratory, Upton, New York 11973, USA
† Department of Physics, University of California at Los Angeles, Los Angeles, California 90095, USA

Nature 1995

Two distinct temperature scales for superconductivity:

$T^*$ as the onset of phase fluctuating Cooper pairs
$T_c$ as the onset of Phase coherence
Sources of Nernst effect

• Quasi-particles (normal state)
• Vortices (mixed state)
• Gaussian fluctuations (short-lived Cooper pairs in the normal state)
• Phase fluctuations (short-lived vortices in the normal state)
But quasi–particle Nernst effect can be large!

\[ N = \frac{\pi^2 k_B^2 T}{3} \frac{\partial \Theta_H}{\partial \epsilon} \bigg|_{\epsilon_F} \]

\[ \nu \sim \left( \frac{\pi^2}{3} \right) \frac{k_B^2 T}{e} \frac{\mu}{E_F} \]

- High mobility
- Small Fermi energy
In underdoped YBCO the Nernst coefficient is negative…

Wang, Li and Ong, 2006

The background signal is negative!
Vortices move from hot to cold.

They point parallel to the magnetic field.

Therefore, the sign of the vortex Nernst signal is preset!

It is positive if $N$ is defined as:

$$N = \frac{E_y}{-\nabla_x T}$$
Quantum oscillations and the Fermi surface in an underdoped high-$T_c$ superconductor

Nicolas Doiron-Leyraud$^1$, Cyril Proust$^2$, David LeBoeuf$^1$, Julien Levallois$^2$, Jean-Baptiste Bonnemaison$^1$, Ruixing Liang$^{3,4}$, D. A. Bonn$^{3,4}$, W. N. Hardy$^{3,4}$ & Louis Taillefer$^{1,4}$
Broken rotational symmetry in the pseudogap phase of a high-$T_c$ superconductor

R. Daou$^1$, J. Chang$^1$, David LeBoeuf$^1$, Olivier Cyr-Choinière$^1$, Francis Laliberté$^1$, Nicolas Doiron-Leyraud$^1$, B. J. Ramshaw$^2$, Ruixing Liang$^{2,3}$, D. A. Bonn$^{2,3}$, W. N. Hardy$^{2,3}$ & Louis Taillefer$^{1,3}$

YBCO $y = 6.67$ $T_c = 66$ K

The negative Nernst signal in YBCO emerges below $T^*$.!!
Fermi-surface reconstruction by stripe order in cuprate superconductors

Both YBCO and EU-doped LSCO Show the same S/T close to p=0.125

Electron pocket’s T_F = 420 K implying S/T ~ 1 µVK^-2
The small electron pocket is the source of the negative Nernst signal in YBCO!

- Mobility = 0.02 T\(^{-1}\)
- Fermi Temperature 420 K
- Both known from quantum oscillations!

Laliberté et al., Nature Commun. 2011
The small electron pocket is the source of the negative Nernst signal in YBCO!
Summary

- Superconducting vortices generate a Nernst signal whenever they are mobile.
- In high-$T_c$ cuprates, mobile vortices generate a Nernst signal in the mixed state.
- In underdoped YBCO, the negative Nernst signal is due to quasi-particles.
III. B
superconducting fluctuations

- Varlamov & Larkin, *Theory of Fluctuations in Superconductors*

Vortices and fluctuations

More thermal fluctuations

More quantum fluctuations
The Ginzburg-Landau theory

\[ F = \int dx \left[ a |\Psi|^2 + \frac{b}{2} |\Psi|^4 + \frac{\hbar^2}{2m^*} |\nabla - i \frac{e^*}{\hbar c} A| \Psi|^2 \right] \]

\( \Psi \) is the order parameter

In a superconductor, it is the density of Cooper pairs!
The Ginzburg-Landau theory

\[ F = \int dx \left[ a |\Psi|^2 + \frac{b}{2} |\Psi|^4 + \frac{\hbar^2}{2m^*} |(\nabla - i \frac{e^*}{\hbar c} A)\Psi|^2 \right] \]

- Above \( T_c \), \( \langle \psi \rangle = 0 \).
- But, instantaneously and locally \( \psi \) is not necessarily zero.
The Ginzburg-Landau theory

\[ F = \int dx \left[ a |\Psi|^2 + \frac{b}{2} |\Psi|^4 + \frac{\hbar^2}{2m^*} |(\nabla - \frac{i}{\hbar c} e^* A)\Psi|^2 \right] \]

The third term provides room for fluctuating superconductivity
The Ginzburg-Landau theory

\[ F = \int dx \left[ a |\Psi|^2 + \frac{b}{2} |\Psi|^4 + \frac{\hbar^2}{2m^*} |(\nabla - i \frac{e^*}{\hbar c} A)\Psi|^2 \right] \]

- In a finite window (in length and in time), \( \psi \) can be finite.
- There are short-lived & local Cooper pairs in the normal state.
- Often called gaussian fluctuations.
Paraconductivity of short–lived Cooper pairs


"AMORPHOUS" BISMUTH FILM
CONDENSED AT 4.2°K
THICKNESS 470±40 Å

Resistivity begins to drop from its normal-state value above $T_c$. 

\[
1 - \frac{R(T)}{R_{\text{res}}} \sim \frac{T_c}{T - T_c}
\]
Paraconductivity of short-lived Cooper pairs

Aslamazov–Larkin fluctuations in 2D

\[ \Delta G = \frac{e^2}{h} \frac{T_c}{16(T - T_c)} \]

Reduced critical temperature

\[ \epsilon = \frac{T - T_c}{T_c} \]

Quantum of electric conductance
Nernst effect due to Gaussian fluctuations of the superconducting order parameter (Usushishkin, Sondhi & Huse, 2002)

In two dimensions, the coherence length, $\xi$, is the unique parameter!

In 2D:

$$\alpha_{xy}^{SC} = \frac{1}{6\pi} \frac{k_B e}{\hbar} \frac{\xi^2}{\ell_B^2}$$

Magnetic length

Quantum of thermo-electric conductance (21 nA/K)
How do the fluctuating Cooper pairs generate a Nernst signal?

• Above $T_c$, the lifetime of the Cooper pairs decrease with increasing temperature.

• Therefore, those pairs which travel from the hot side along the cold side live longer!
How short-lived Cooper pairs generate charge conductivity and off-diagonal thermoelectric conductivity

\[ \sigma_{xx} = \frac{e^2}{h} \frac{T_c}{16(T - T_c)} \propto \xi^2 \propto \frac{1}{\epsilon} \]

Reduced temperature:

\[ \epsilon = \frac{T - T_c}{T_c} \]

\[ \alpha_{xy} = \frac{1}{6\pi} \frac{k_B e}{\hbar} \frac{\xi^2}{(\ell_B)^2} \propto \frac{1}{\epsilon} \propto B \]

- Each is expressed in ts quantum units.
- Both are proportional to the 2D fluctuating volume (\(\xi^2\)).
- Off-diagonal thermoelectric conductivity is proportional to B.
The coherence length

- Diverges at $T_c$
- Attains a finite value at zero temperature
- Dies out slowly in the normal state
The coherence length

- The radius of a superconducting vortex
- The average size of a Cooper pair
- The magnitude of the upper critical field.
- The size of Gaussian fluctuations.

In a clean BCS superconductor

\[ \xi_0 = \frac{2\hbar v_F}{\pi \Delta} \]

Usually longer than the interelectron distance, if not, then a BEC transition.
Observation of the Nernst signal generated by fluctuating Cooper pairs

A. POURRET¹, H. AUBIN¹*, J. LESUEUR¹, C. A. MARRACHE-KIKUCHI², L. BERGÉ², L. DUMOULIN² AND K. BEHNIA¹*

¹ Laboratoire de Physique Quantique (CNRS-LIPPS), ESPCI, 10 Rue Vauquelin, 75231 Paris, France
² CSNSM, IN2P3-CNRS Bâtiment 108, 91405 Orsay, France
* e-mail: Herve.Aubin@espci.fr; Kamran.Behnia@espci.fr

The normal state has no Nernsy signal because, it …

• is dirty
• has a large carrier density
• is uncorrelated

Nature Physics, 2006
Amorphous superconductors

- Amorphous bismuth
- MoGe
- Nb$_x$Si$_{1-x}$
- Nb$_x$Ge$_{1-x}$
- InO$_x$
- TiN

- They all host a superconductor-to-insulator transition
Superconductor-insulator transition in amorphous bismuth

Goldman and co-workers
A field-induced quantum phase transition

InO$_x$ Sahar et al.
Superconductivity in $\text{Nb}_{0.15}\text{Si}_{0.85}$ thin films

The normal state is a simple dirty metal: $l_e \sim a \sim 1/k_F$!
The superconducting transition temperature shifts with thickness!
Field–induced Superconductor–Insulator phase transition

Aubin PRB’05
Nernst effect across the resistive transition

- A large vortex signal below $T_c$
- A long tail above $T_c$
A signal distinct from the vortex signal
A thinner sample with a lower $T_c$.

Nernst signal detected at a temperature 30 times larger than $T_c$!
Deep into the normal state!
The Nernst signal of the normal electrons is negligible!

Even at 6K:
The expected normal state contribution is three orders of magnitude smaller than $n/T$!
Comparison with theory

Theory:

\[ \alpha_{xy} = \frac{1}{6\pi} \frac{k_B e}{h} \frac{\xi^2}{(\ell_B)^2} = \frac{B}{6\pi} \frac{k_B e^2}{\hbar^2} \frac{\xi^2}{(\ell_B)^2} \]

Experiment measures the Nernst coefficient \( \nu \)

\[ \nu = \frac{E_y}{(-\nabla T)B} = \frac{\alpha_{xy} \sigma_{xx} - \alpha_{xx} \sigma_{xy}}{\sigma_{xx}^2 + \sigma_{xy}^2} \]

In our case: \( \sigma_{xx} > 10^3 \sigma_{xy} \) and \( \sigma_{SC} < 10^{-1} \sigma_{xx} \) (when \( T > 1.1 T_c \))

\[ \nu = \frac{\alpha_{xy}}{\sigma_{xx}} \quad \quad \alpha_{xy} = \frac{\nu}{R_{sq}} \]

Both \( \nu \) and \( R_{sq} \) are measured by experiment!
Estimating the superconducting coherence length

In a 2D dirty superconductor:

\[
\xi_d = \frac{1}{\sqrt{\varepsilon}} \cdot 0.36 \sqrt{\frac{3}{2} \frac{\hbar v_F \ell}{k_B T_c}}
\]
The shortest link between data and $v_F/e$

$$v_F \ell = 3 \frac{k}{\gamma_e T} = \left( \frac{\pi k_B}{e} \right)^2 \frac{\sigma}{\gamma_e}$$

Using specific heat and resistivity data, this yields:

$$v_F \ell = 4.35 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$$

Therefore, we have everything to estimate the coherence length.
Comparison with theory

Experiment:
\[ \frac{\nu}{R_{square}} = \frac{\alpha_{xy}^{SC}}{B} \]

Theory:
\[ \alpha_{xy}/B = \left( \frac{k_B e^2}{6\pi \hbar^2} \right) \xi_d^2 \]

All parameters from experiment, none adjustable.
A first conclusion

- The magnitude of the experimentally resolved signal is in agreement with theory close to $T_c$.
- It falls down a faster than $1/e$ for large $e$.
- Even at $T \sim 2T_c$, the difference between theory and experiment is less than a factor of 2.
The Nernst signal survives at all field scales associated with the destruction of superconductivity!

Superconducting fluctuations survive above $H_{c2}$!

\[ B^P = 1.84T_c \]

\[ B^{\text{orb}} = \Phi_0 / 2\pi\xi^2 \]
Zero-field and finite field theory

The USH theory

$$\alpha_{xy} = \frac{1}{6\pi} \frac{k_B e}{\hbar} \frac{\xi^2}{(\ell_B)^2}$$

It is valid only in the weak-field limit:

$$\ell_B \gg \xi$$

In this limit, the Cooper pairs are smaller than the magnetic length!

What happens when the magnetic length becomes shorter than the correlation length?
The Nernst signal is damped at high-field.
The decay of the fluctuating signal with temperature and magnetic field.
The ghost critical field

Below $T_c$, there is an [orbital] upper critical field:

$$\ell_B (B) = \xi(T)$$

It corresponds to the boundary:  

Above $T_c$, the same boundary defines the ghost critical field.
Experimental ghost critical field

Contour plot of $N = -E_y / (dT/dx)$
A unique correlation length

Contour plot of the Nernst coefficient $\nu = N/B$

$$\xi_d = \frac{1}{\sqrt{\epsilon}} \times 0.36 \sqrt{\frac{3}{2}} \frac{\hbar v_F l}{k_B T_c}$$

$$\epsilon = \ln \left( \frac{T}{T_c} \right)$$

$$l_B = \sqrt{\frac{\hbar}{2eB}}$$
Ghost critical field vanishes at $T_c$
The decay of the fluctuating signal with temperature and magnetic field
The decay of the fluctuating signal with temperature and magnetic field.
Theory at finite field and high temperature

FIG. 3: (Color online) Comparison with experiment. Circles: experimental data for $\lim_{H \to 0} \beta^{xy} / H$ vs. $\epsilon = \ln T / T_c$ obtained for the 12.5-nm-thick Nb$_{0.15}$Si$_{0.85}$ film [10]. Dashed line: theoretical prediction for the strictly 2D geometry. Solid line: theoretical prediction for the real sample [10] with the 2D-3D crossover taken into account.

Theory at finite field and high temperature

Resistivity detects these Gaussian fluctuations too!
Resistivity detects these Gaussian fluctuations too!

\[ \Delta G (S) = \frac{e^2}{16h} \frac{T_c}{(T-T_c)} \]

Aslamazov-Larkin

But paraconductivity is only a small fraction of total conductivity and the temperature dependence of conductivity in absence of superconductivity is unknown!
Why a dirty superconductor?

Compare the Ginzburg–Landau time scale and the quasi–particle lifetime:

\[ \tau_{GL} = \tau_{qp} \left( \frac{x}{l_e} \right)^2 \]

\[ \tau_{GL} > \tau_{qp} \]

In a wide temperature range above \( T_c \), Cooper pairs live much longer than quasi–particles and dominate the Nernst response!
III. c
Correlated Superconductors
Conventional superconductors

FIG. 1. The conventional picture of superconductivity: (a) In the BCS model, superconductivity arises from the attractive electron-electron interaction mediated by phonon scattering. (b) The excitations from the Cooper pair ground state exhibit an energy gap $\Delta$ that is (very nearly) isotropic in $k$ space.
Unconventional superconductors

- The order parameter of the unconventional superconductors is less symmetric than the Fermi surface of the mother metal.

- The gap function can vanish along particular orientations (nodes).
Pairing symmetries

Van Harlingen
Rev. Mod. Phys.
1995
Correlated superconductors

- The normal state of a correlated superconductor is a strongly-correlated metal

- A correlated superconductor is a natural candidate for unconventional superconductivity
Families of correlated superconductors

- Heavy-fermion superconductors
- Organic superconductors
- Cuprate superconductors
- Iron-based superconductors
High $T_c$ cuprates
Quantum oscillations and the Fermi surface in an underdoped high-$T_c$ superconductor

Nicolas Doiron-Leyraud\textsuperscript{1}, Cyril Proust\textsuperscript{2}, David LeBoeuf\textsuperscript{1}, Julien Levallois\textsuperscript{3}, Jean-Baptiste Bonnemaison\textsuperscript{1}, Ruixing Liang\textsuperscript{3,4}, D. A. Bonn\textsuperscript{3,4}, W. N. Hardy\textsuperscript{3,4} & Louis Taillefer\textsuperscript{1,4}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{A small Fermi surface
Highly mobile electrons
Only seen in YBCO}
\end{figure}

Electron pockets in the Fermi surface of hole-doped high-$T_c$ superconductors

David LeBoeuf\textsuperscript{1}, Nicolas Doiron-Leyraud\textsuperscript{1}, Julien Levallois\textsuperscript{2}, R. Daou\textsuperscript{1}, J.-B. Bonnemaison\textsuperscript{1}, N. E. Hussey\textsuperscript{3}, L. Balicas\textsuperscript{4}, B. J. Ramshaw\textsuperscript{5}, Ruixing Liang\textsuperscript{5,6}, D. A. Bonn\textsuperscript{5,6}, W. N. Hardy\textsuperscript{5,6}, S. Adachi\textsuperscript{7}, Cyril Proust\textsuperscript{2} & Louis Taillefer\textsuperscript{1,6}
YBa$_2$Cu$_3$O$_{6.67}$ ($T_c = 66$ K)

$S/T = 0.4 \ \mu$V/K$^2$         \quad T_F = 1060 \ K

Electron pocket’s $T_F = 420$ K
Both YBCO and EU-doped LSCO Show the same S/T close to p=0.125
The small electron pocket is the source of the negative Nernst signal in YBCO!

Laliberté et al., Nature Commun. 2011

- Mobility = 0.02 T^{-1}
- Fermi Temperature 420 K
- Both known from quantum oscillations!
The small electron pocket is the source of the negative Nernst signal in YBCO!
Broken rotational symmetry in the pseudogap phase of a high-$T_c$ superconductor

R. Daou, J. Chang, David LeBoeuf, Olivier Cyr-Choinière, Francis Laliberté, Nicolas Doiron-Leyraud, B. J. Ramshaw, Ruixing Liang, D. A. Bonn, W. N. Hardy & Louis Taillefer

YBCO $y = 6.67$, $T_c = 66$ K

The negative Nernst signal in YBCO emerges below $T^*$ !!!???
The Nernst response is extremely anisotropic in the pseudogap state!
But becomes isotropic in the zero-temperature limit.

\[ \Delta T_{\parallel}^{a} \]
Organic superconductors

\[ X = \text{Cu}[^{14}N\text{(CN)}_2]^+ \text{Cl}^- \]
\[ X = \text{Cu}[^{14}N\text{(CN)}_2]^+ \text{Br}^- \]
\[ X = \text{Cu}\text{NCS}_2^- \]

- Paramagnetic insulator
- Fermi liquid
- Mott insulator
- Superconductor

\(\kappa-(\text{BEDT-TTF})_2X\)

Temperature (K)
Pressure (kbar)
Increasing \(t/U\)
LETTERS

Fluctuating superconductivity in organic molecular metals close to the Mott transition

Moon-Sun Nam\textsuperscript{1}, Arzhang Ardavan\textsuperscript{1}, Stephen J. Blundell\textsuperscript{1} & John A. Schlueter\textsuperscript{2}

Organic superconductors

$\kappa-(\text{BEDT-TTF})_2\text{Cu}(\text{N(CN)}_2\text{Br})$  

$\kappa-(\text{BEDT-TTF})_2\text{Cu}(\text{NSC})_2$
Organic superconductors

\( \kappa-(\text{BEDT-TTF})_2\text{Cu(NSC)}_2 \)

Sasaki et al., 1999
Organic superconductors

Logonov et al., 1999
115 superconductors

Paglusio 2002
The phase diagram

Flouquet 2010

Figure 14. \((H,T,P)\) phase diagram of CeRhIn\(_5\) compared to the one proposed for the high \(T_c\) superconductor [77, 78].
Thermoelectric Response Near a Quantum Critical Point: The Case of CeCoIn$_5$

K. Izawa,$^{1,2,3}$ K. Behnia,$^4$ Y. Matsuda,$^{3,5}$ H. Shishido,$^{5,6}$ R. Settai,$^6$ Y. Onuki,$^6$ and J. Flouquet$^2$

$^1$Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo, 152-8551 Japan
$^2$DRFMC/SPSMS, Commissariat à l'Energie Atomique, F-38042 Grenoble, France
$^3$Institute for Solid State Physics, University of Tokyo, Kashiwa, Chiba 277-8581, Japan
$^4$Laboratoire Photons Et Matière (CNRS), ESPCI, 75231 Paris, France
$^5$Department of Physics, Kyoto University, Kyoto 606-8502, Japan
$^6$Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan

(Received 16 April 2007; published 4 October 2007)

CeCoIn$_5$ ($T_c=2.2$ K) \hspace{1cm} S/T =12 µVK$^{-2}$ \hspace{1cm} $T_F=35$ K
Field–induced quantum critical point in CeCoIn$_5$

Paglione et al., 2003, Bianchi et al. 2003
Detected by resistivity and specific heat

Paglione 2003
Detected by resistivity and specific heat

Bianchi 2003
Nernst effect in the vicinity of QCP

Izawa 2007
logarithmic color plot of $\nu/T$
Signatures of a small [vanishing?] $E_F$ near QCP

A from Paglione et al. 2003
$\gamma$ from Bianchi et al. 2003
$v/T$ from Izawa 2007
Iron-based superconductors

Fig. 11 (color online) H. Chen et al. (2009), T_s and T_{SDW} stay equal vs x. Johrendt and Pöttgen (2009) find that T_{SDW} is suppressed at x=0.3, however both groups find that T_{SDW} does not join the superconducting dome.

Fig. 12 (color online) Nandi et al. (2010). Note the factor of two between x in their notation vs the y used here and that T_s and T_{SDW} indeed intersect the superconducting dome.
The 11 family \((\text{FeTe}_x\text{Se}_{1-x})\)

FIG. 3. (Color online) In plane resistivity of \(\text{FeTe}_x\text{Se}_{1-x}\) crystals. Measured compositions are given in Table I.
The case of $\text{Fe}_{1+y}\text{Se}_{0.4}\text{Te}_{0.6}$

Pourret et al., PRB (2010)
The case of $\text{Fe}_{1+y}\text{Se}_{0.4}\text{Te}_{0.6}$ ($T_c = 14\, \text{K}$)

$S/T = -2.8\, \mu\text{VK}^{-2}$ \hspace{1cm} $T_F = 151\, \text{K}$
What is striking in Fe$_{1+y}$Se$_{0.4}$Te$_{0.6}$?

Comparison with a borocarbide superconductor

<table>
<thead>
<tr>
<th></th>
<th>Fe$<em>{1+y}$Se$</em>{0.4}$Te$_{0.6}$</th>
<th>LuNi$_2$B$_2$C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_c$ (K)</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>$\Delta_0$ (meV)</td>
<td>1.7</td>
<td>1.9</td>
</tr>
<tr>
<td>$\gamma$ (mJ K$^{-1}$mol$^{-1}$)</td>
<td>23</td>
<td>19</td>
</tr>
<tr>
<td>S/T</td>
<td>-2.8</td>
<td>-0.22</td>
</tr>
<tr>
<td>$dH_{c2}/dT$ (KT$^{-1}$)</td>
<td>12</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Both S/T and $dH_{c2}/dT$ are magnified by an order of magnitude as a consequence of heavy mass and small carrier density!

\[ n = 1 \times 10^{21} \text{ cm}^{-3} \]
\[ m^* \sim 30 \text{ m}_e \]
A set of self-consistent parameters

Measured

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (m$\Omega$ cm)</td>
<td>0.35</td>
</tr>
<tr>
<td>$\gamma$ (mJ K$^{-1}$mol$^{-1}$)</td>
<td>23</td>
</tr>
<tr>
<td>$S/T$ ($\mu$V K$^{-2}$)</td>
<td>-2.8</td>
</tr>
<tr>
<td>$\Delta_0$ (meV)</td>
<td>1.7</td>
</tr>
<tr>
<td>$dH_c^2/dT$ (KT$^{-1}$)</td>
<td>12</td>
</tr>
</tbody>
</table>

Deduced

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l$ (nm)</td>
<td>2.7</td>
</tr>
<tr>
<td>$\xi$ (nm)</td>
<td>1.7</td>
</tr>
<tr>
<td>$m^*$ ($m_e$)</td>
<td>29</td>
</tr>
<tr>
<td>$v_F$ (km s$^{-1}$)</td>
<td>12</td>
</tr>
</tbody>
</table>

\[ m^* = \Delta_0 \]
\[ \xi = 1.7 \text{ nm} \]
\[ \xi = 1.6 \text{ nm} \]
$\text{Fe}_{1+y}\text{Se}_{0.4}\text{Te}_{0.6}$ is a low-density correlated superconductor

<table>
<thead>
<tr>
<th>$n^{1/3}$ (nm)</th>
<th>1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l$ (nm)</td>
<td>2.7</td>
</tr>
<tr>
<td>$\xi$ (nm)</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Barely clean ($\xi > l$)

Size of Cooper pairs very close to interelectron distance

<table>
<thead>
<tr>
<th>Superconductor</th>
<th>$n$ (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{URu}_2\text{Si}_2$</td>
<td>$6 \times 10^{21}$</td>
</tr>
<tr>
<td>$\text{InO}_x$</td>
<td>$4 \times 10^{21}$</td>
</tr>
<tr>
<td>$\text{FeSe}<em>{0.4}\text{Te}</em>{0.6}$</td>
<td>$1 \times 10^{21}$</td>
</tr>
<tr>
<td>$\text{Boron-doped diamond}$</td>
<td>$5 \times 10^{20}$</td>
</tr>
<tr>
<td>$\text{SrTiO}_3$</td>
<td>$10^{20}$</td>
</tr>
</tbody>
</table>
The Moriya–Ueda plot

In 2D, equivalent to the Uemuera plot $T_c \propto n_s/m^*$

Nernst plots

\[ \text{Fe}_{1+y}\text{Se}_{0.4}\text{Te}_{0.6} \]

The Ginzburg number

\[ \frac{k_B T_c}{\frac{1}{2} N(0) \Delta^2 \xi^3} \]

is large and this leads to a wide window of fluctuations.
Past Collaborators


Hervé Aubin

Cigdem Capan
[1999–2002]

Saco Nakamae
[2000–2002]

Romain Bet
[2001–2004]

Alexandre Pourret
[2004–2007; 2009]

Cyril Proust
(Toulouse)
Current Collaborators

Zengwei Zhu

Benoit Fauqué

Aurélie Callaudin

Yuki Fuseya (Osaka)

Xiao Lin

Woun Kang (Seoul)
Mentors

Didier Jaccard

Jacques Flouquet