Nernst effect

590B

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• Nernst effect
Nernst-Ettingshausen effect (1\textsuperscript{st} NE)

\[ E_y = N \frac{1}{B} \frac{dT}{dx} \]

Nernst-Ettingshausen effect (2\textsuperscript{nd} NE)

\[ \frac{dT}{dy} = PI_x B_z \]

Graz 1887
Ludwig Boltzman and coworkers

Thesis 1887: Electromotive forces produced by magnetism in heated metal plates

Third law of thermodynamics (Nobel prize 1920)
Nernst glower
Bernstein-Siemens-Nernst electric piano
The Hall effect is given by the formula:

\[ V_H = R_H \frac{IB}{d} \]

This formula represents the transverse voltage \( V_H \) produced by a longitudinal current \( I \) in a magnetic field \( B \). The Hall voltage is proportional to the magnetic field and the product of the current and mass density, divided by the width of the current flow.
Nernst effect or 1\textsuperscript{st} Nernst-Ettingshausen effect

\[ N = \frac{E_y B_z}{dT / dx} \]

Transverse voltage
Longitudinal heat current
Magnetic field
Ettingshausen effect
or 2\textsuperscript{nd} Nernst-Ettingshausen effect

\[ \Delta T = P \frac{BI}{d} - \frac{1}{2} \frac{\rho I^2}{d^2 \kappa} \]

- \( \Delta T \): Transverse thermal gradient
- \( B \): Magnetic field
- \( I \): Longitudinal electrical current
- \( q \): Sample thickness
- \( \kappa \): Thermal conductivity
- \( \rho \): Electrical resistivity

Can be used for thermoelectric cooling
Closer look
Nernst effect

Hall effect: Lorenz force
Flowing charges in B

NE Steady state: no charge flow!
E_s compensates \( \nabla T \) force
N=0?
We met this situation before.
Where?

Magnetoresistance,
cyclotron orbit curvature is
compensated by Hall voltage
to first degree effect is zero

Nernst effect is second order effect
DISTRIBUTION of velocities of carriers,
qE_s compensates average \( v_D \),
but not hotter and colder than average

In SIMPLE metals for "good scattering"
N is negligibly small
Nernst effect in gold \( \sim 0.1 \text{ nV/KT} \)
Nernst effect in anisotropic metals

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“Bad scattering”

Anisotropy notably increases Nernst effect

FIG. 2. Magnetic-field dependence of the raw Nernst signal at $T=250$ K showing the linear variation with the applied field strength.

FIG. 3. Temperature dependence of the Nernst coefficient $Q$ of the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin-film sample. $Q$ goes to zero just above $T_c$, but increases rapidly at lower temperature, reflecting the large contribution from superconducting fluctuations.

"Increased" $N \sim 5 \text{nV/KT}$!
Measurement of Nernst effect

Typical numbers

**Metals**
Good scattering ???
Anisotropic scattering 5 nV/kT
\[ V < 10 \text{ nV} \]

**Semiconductors**
\[ n \sim 10^{16} - 10^{24} \text{ m}^{-3} \]
\[ V \sim 1 - 100 \text{ } \mu\text{V} \]

Very demanding measurements from thermal stability and electrical noise point of view

Ideologically similar to Thermopower measurements
Measurements

Nernst signal is defined as odd part of $S_{xy}$ in field

$$S_{xy} = S_{\text{nonequipotential}} + S_{\text{MR}} + S_N$$

Measurements in positive and negative fields, $S_{xy}(H) - S_{xy}(-H) = 2S_N$

Fixed temperature $+H$ to $-H$ sweep
Time consuming

Strict requirements for $T$-drift, $S_{xy}(\delta T) << S_{xy}(H)$
Low-frequency method for magnetothermopower and Nernst effect measurements on single crystal samples at low temperatures and high magnetic fields

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\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{diagram.png}
\caption{Diagram of the measurement holder (the outer diameter of the cylindrical copper holder is 10 mm). A: Cu heat sink, B: quartz blocks, and C: heaters. 1: thermopower leads of sample, 2: Chromel–Au(Fe0.07%) thermocouples for ΔT leads, 3: Nernst voltage leads of sample, and 4: thermopower leads of reference YBCO sample.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figures.png}
\caption{(a) Heater currents and (b) ΔT(ΔV) as a function of the sine T period of the heating cycle is 30 s and the corresponding periods of oscillation of temperature gradient and thermopower signal are 15 s (c) S vs frequency method used to determine the optimum frequency range for the TEP measurements.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{magnetothermopower.png}
\caption{(a) ΔV_1, ΔV_2, and ΔV_3 versus magnetic field for α-(BEDT–TTF)$_2$K$_2$Hg(SCN)$_4$ at T = 0.7 K. (b) Derived magnetothermopower results. Note the narrow range of field in (a), which corresponds to only a few quantum oscillations in (b).}
\end{figure}
Why bother measuring Nernst effect?

• Additional insight into multiple carrier conductors
• Anomalous scattering, easy to detect sharp features in $\frac{\partial \sigma(\varepsilon)}{\partial \varepsilon}$
• Exotic scattering in magnetic systems

K. Behnia

• Thermoelectricity as a probe of exotic states of correlated electrons is still largely underexplored.
Nernst effect in superconductors

Nernst Effect and Flux Flow in Superconductors. I. Niobium*

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N is big in the mixed state of SC Flux quanta respond to grad T by thermal diffusion generate Seebeck and Nernst voltages

Fig. 2. Transverse voltage $U_{12}$ versus magnetic field for different temperature gradients. The temperature at each curve is the value at the heater. (Specimen 4; temperature at heat sink = 4.2°K.)
Nernst effect in superconductors


REVIEW ARTICLE
Superconductors in a temperature gradient

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Same big in high-Tc cuprates
But in a broader T-range

Figure 3. Resistivity $\rho$ (a) and normalized Nernst electric field $E_y/V_x T$ (b) versus temperature for an epitaxial c-axis-oriented $YBa_2Cu_3O_{7-\delta}$ film at different magnetic fields ($B \parallel c$).
Vortex-like excitations and the onset of superconducting phase fluctuation in underdoped La_{2-x}Sr_xCuO_4

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Figure 1 Nernst signals. a. The Nernst signal $E_N$ (normalized to unit gradient) versus $H||c$ in La$_{2-x}$Sr$_x$CuO$_4$ (sample 3, $x = 0.10$) at temperatures 12–35K. b. The Nernst signal from 40 to 200K. Above 20K the applied gradient is 5 K cm$^{-1}$, while below 20K it is half as large. When vortex pinning is large ($T < 25$K), $E_N$ is zero over a range of $H < H_a$. Above 140K, the curves tend asymptotically to a straight line of negative slope.

Figure 4 Contour plot of $(\nu - \nu_c)$ versus $x$ in the phase diagram of LSCO. The contour plot displays how high in $T$ the vortex-like excitations extend for each value of $x$. The upper solid line $T_{onset}$ is the contour set by our resolution. The pseudogap $T^*$ estimated from heat capacity is about a factor of two larger than $T_{onset}$. Values of $T_c$ in our samples (circles) match the $T_c$ line (lower solid line) from Takagi et al. We note that the $T_e$ line is roughly similar to the contour line $\nu = 1 \mu V/KT$.

Claims:
Nernst effect is too big for a metal
Superconducting vortices above $T_c$
Preformed pairs scenario
Can Nernst effect be big otherwise?

To have big MR you need $V_H = 0$

Q. What should we have $= 0$ to get big Nernst effect?

A. $S = 0$

Compensation of different carrier types

No compensation for cyclotron orbit curvature

When $S=0$ there is no restoring force and there is always a current of two carrier types in the same direction
Contrary to Hall effect
Contributions of $+q$ and $-q$
Sum up in ambipolar Nernst effect

Q. What is the difference?

One carrier type: Nernst is second order effect
Two carrier types: Nernst effect is FIRST order effect
Nernst effect Ge: big

Semiconductors
First observation

N is very big in narrow gap semiconductors

Number of unknowns = number of equations
To solve transport completely you want to measure
Single carrier type: resistivity + Hall
Second carrier type: + Seebeck + Nernst

Fig. 2. Experimental Nernst coefficient, $B$, in $n$- and $p$-type germanium of different resistivities, as a function of temperature between 300 and 750 K, measured at 2100 and 9000 gauss.
Not negligible even in metallic systems!

Ambipolar Nernst Effect in NbSe$_2$

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FIG. 2. Upper panel: thermopower ($S$) of NbSe$_2$ at $H = 0$ (solid circles) and $H = 5$ T (open circles). Lower panel: thermal conductivity divided by temperature (solid circles) as a function of temperature. Also shown is the charge conductivity ($\sigma$) at $H = 0$ (solid squares) and at $H = 5$ T (open squares) multiplied by the constant $L_0$ (see text).

FIG. 3. Upper panel: the Nernst coefficient as a function of temperature at $H = 0$ and $H = 5$ T. The inset compares the field dependence of the Nernst signal at three different temperatures. Lower panel: the temperature dependence of the Hall coefficient measured at $H = 5$ T. Inset: a schematic plot of the three-band Fermi surface in NbSe$_2$ as observed by angular-resolved photoemission spectroscopy (ARPES) [11].
Nernst effect is big when weak field MR is big:
Compensation+ high mobility

Bi metal 200% MR in 2T at room temperature

FIG. 1 (color online). (a) Thermal conductivity, $\kappa$ of the Bi single crystal. Solid line represents a $aT + bT^3$ fit (see text). Inset compares the magnitude of $\kappa(3K)$ of the sample of this study (solid circle) with those reported in Ref. [15] (open circles) as a function of mean diameter. (b) Resistivity of the same sample at zero field and in presence of a field of 0.1 T.

FIG. 2. The temperature dependence of the absolute value of the Nernst coefficient of the bismuth single crystal for two different orientations of the magnetic field. The solid line represents a linear function $\alpha T$ with $\alpha = \frac{1}{e^2 \epsilon_f B} = 0.38$ mV K$^{-1}$ T$^{-1}$ (see text and Table I). Both this function and the low-temperature data are displayed in the inset as a $\nu/T$ vs $T$ plot.
FIG. 3 (color online). The magnitude of the Nernst coefficient in bismuth compared to what is found in some other metals [4,5,7,8,12].

K. Behnia group
Giant Nernst Effect and Lock-In Currents at Magic Angles in \((\text{TMTSF})_2\text{PF}_6\)

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FIG. 2. Angular dependence of the Nernst signal at 2, 1, and 0.2 K, \(B = 7.5\) T showing the rapid growth with lower temperature. We have used \(N = \frac{S(B) - S(-B)}{2}\) as our definition for the Nernst signal.

FIG. 4. Looking down the TMTSF chains. For the field near the \(b + c\) direction the current flows only between the chains separated by \(b + c\). The Lorentz force then produces a force along \(a\) in the first figure, along \(-a\) in the last figure, and no force in the middle figure when the field and the current are parallel. Note that here we use an orthorhombic approximation.
Reading:
General
J. M. Ziman Principles of the theory of solids

Nernst effect in superconductors, review

Nernst effect in exotic materials
K. Behnia, virtual lecture at hvar05.ifs.hr/workshop/work_lectures.html

Review articles on physics of thermal and thermoelectric phenomena