Physica C 174 (1991) 373–376
North-Holland

Nernst effect in high-T_c superconductors

H. Lengfellner and A. Schnellbögl
Institut für Angewandte Physik, Universität Regensburg, W-8400 Regensburg, Germany

Received 13 December 1990

In this paper we present a description of the Nernst electric field E generated by forced flux tube motion due to a temperature gradient ∇T. Depending on the value of ∇T with respect to a critical gradient ∇T_{crit}, we find for $\nabla T/\nabla T_{crit} \ll 1$ a regime $E \propto \nabla T$, in close analogy to the regime of thermally activated flux flow in transport current measurements (characterized by an electric field proportional to the transport current). The theory for $\nabla T < \nabla T_{crit}$ is applied to an analysis of experimental results obtained for polycrystalline $Tl_2Ba_2CaCu_2O_x$ films. From the temperature dependence of the Nernst field we derive activation energies for flux depinning.

Thermomagnetic effects in high-T_c superconductors have recently been observed by several groups [1–3]. From investigation of the Nernst effect in polycrystalline $Tl_2Ba_2CaCu_2O_x$ films using pulsed laser heating to induce temperature gradients in the film [1], activation energies for depinning of flux tubes have been derived assuming thermally activated flux motion. A Nernst effect was also observed in epitaxial Y–Ba–Cu–O films [2] by continuous heating [4]. From measurement of the Nernst field and the film resistivity due to flux motion, the transport entropy of flux tubes near T_c has been estimated. The transport entropy has also been investigated in a $YBa_2Cu_3O_7$ single crystal, using the Ettingshausen effect [3]; from measurements of the entropy flow the transport line energy of a vortex has been determined. In this paper, we develop a theory to describe flux motion due to a temperature gradient and derive an expression for the Nernst electric field. We then use the theory for an analysis of experimental data reported in ref. [1].

The electric field generated by flux motion is given by $\boldsymbol{E} = (1/c)\boldsymbol{B} \times \boldsymbol{v}$ [5], where $\boldsymbol{B}$ is the magnetic field in the material and $\boldsymbol{v}$ the velocity of $\boldsymbol{B}$ with respect to the material. For flux hopping transverse to $\boldsymbol{B}$, with hopping rate ν and hopping length l, $E = (1/c)B\nu l$. For a derivation of E we follow a theory given by Brandt [6] for the case that the driving force on flux tubes is the Lorentz force due to a transport current. Instead of the Lorentz force we regard the thermal force $\boldsymbol{F}_{th} = -\nabla T\, SL$ [7] that is due to a temperature gradient ∇T and a transport entropy SL of a flux tube, where S is the transport entropy per unit length and L is the flux tube length. For the net jump rate which is the difference of jump rates along and against the driving force we find then, using Andersons model of thermal activated hopping [8],

$$\nu = \nu_0 \exp\left[-\left(\frac{kT_a - \nabla T\cdot SLl}{kT}\right)\right] - \nu_0 \exp\left[-\left(\frac{kT_a + \nabla T\cdot SLl}{kT}\right)\right], \qquad (1)$$

where kT_a is an activation energy and ν_0 an attempt frequency. At a critical temperature gradient $\nabla T_{crit} = kT_a/(SLl)$ the pinning energy and the work done by the thermal force over the hopping length l are equal. With this expression we find

$$E = \frac{2Bl\nu_0}{c} \exp\left(-\frac{T_a}{T}\right) \sinh\left(\frac{T_a \nabla T}{T \nabla T_{crit}}\right). \qquad (2)$$

For a small argument of sinh, i.e. $\nabla T/\nabla T_{crit} \ll 1$, this expression can be simplified to

$$E = \frac{2Bl\nu_0}{c} \frac{T_a \nabla T}{T \nabla T_{crit}} \exp\left(-\frac{T_a}{T}\right). \qquad (3)$$

Our treatment shows therefore that for small driving

0921-4534/91/$03.50 © 1991 – Elsevier Science Publishers B.V. (North-Holland)

forces, the Nernst field is proportional to the driving force (i.e. proportional to ∇T) and, furthermore, to $\exp(-T_a/T)$. This regime of flux motion can be regarded as analogue of the regime of thermally assisted flux flow (TAFF) [9] in transport current measurements characterized by a field proportional to the transport current.

For $\nabla T/\nabla T_{crit} \approx 1$ we obtain from eq. (2)

$$E = \frac{Blv_0}{c} \exp\left[\frac{T_a}{T}\left(\frac{\nabla T}{\nabla T_{crit}} - 1\right)\right], \qquad (4)$$

where an exponential dependence of E on ∇T is obtained as analogue to the regime of current induced flux creep [6]. At gradients $\nabla T \gg \nabla T_{crit}$ a regime of viscous flux motion will be reached described by $E = \nabla T \cdot SL(B/c)\eta$ (regime of flux flow [6]), where η is the viscosity of the vortex motion. So far, we have shown that a temperature gradient ∇T can be used to induce a driving force on flux tubes in a similar way as a transport current I via Lorentz forces. The Nernst field should disappear above T_c, when the vortex structure is destroyed. Use of ∇T instead of I may be favourable because the electric field generated by the Lorentz force cannot be easily distinguished from electric fields due to other resistive mechanisms. In the following we present an analysis of measurements of the Nernst effect in $Tl_2Ba_2CaCu_2O_x$ films [1].

In our experiment the surface of a film was heated by a laser pulse (wavelength $\lambda \simeq 10$ µm, pulse duration $\simeq 100$ ns) and a strong temperature gradient perpendicular to the film surface was obtained. A magnetic field $B \sim 0.1$ T was applied parallel to the film surface (fig. 1(a)). Signals were recorded with a fast storage oscilloscope. Two signal pulses corresponding to opposite directions of the magnetic field are shown in fig. 1(b). The signals show a fast increase (as fast as the laser pulse), and a slow decrease in the range of several µs. As the Nernst field is proportional to ∇T, the signals indicate the buildup and decay of a temperature gradient across the film. The height of the signals in dependence of laser pulse energy density E_P is plotted in fig. 2, for various initial sample temperatures T_I (i.e. the sample temperature before laser pulse injection). The signals show an increase depending on the value of T_I, with increasing slope at higher T_I, and a saturation at about

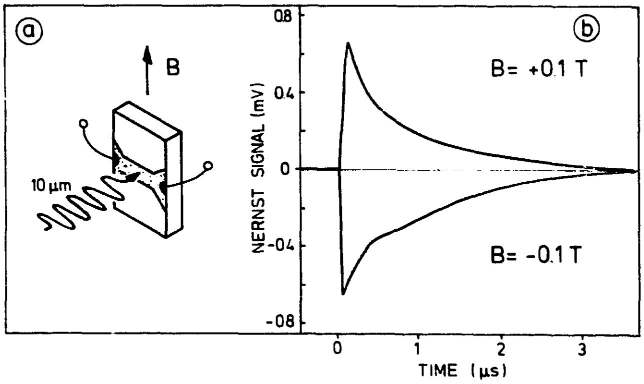

Fig. 1. (a) Experimental arrangement and (b) time resolved signals corresponding to opposite directions of the magnetic field. The initial film temperature was $T_I = 30$ K, the laser pulse energy was $E_P = 8$ mJ/cm^2.

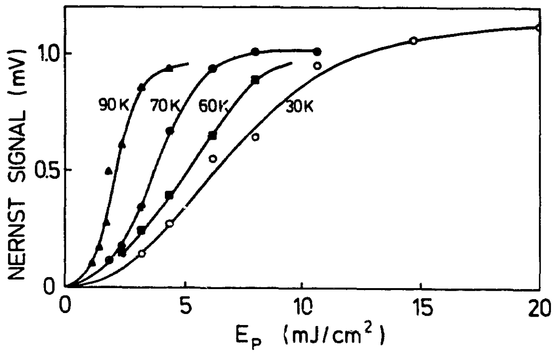

Fig. 2. Signal height vs. pulse energy density E_P, for various initial temperatures T_I. The saturation at high E_P indicates surpass of T_c in parts of the film.

the same maximum value for all T_I. The saturation indicates that for high pulse energies T_c is surpassed in parts of the film.

From a model of heat propagation and using thermal constants we find for the temperature gradient $\nabla T = (1/d)A(T_I)\ E_P$ and for the film temperature near the film substrate interface $T = B(T_I)E_P + T_I$ with film thickness $d \simeq 10^{-4}$ cm, $A(60\ K) \simeq 2\times10^3$ K cm^2/J and $B(60\ K) = 3.5\times10^3$ K cm^2/J [1] at about 100 ns after laser pulse injection. We estimate a maximal temperature gradient $\nabla T = 10^4$–10^5 K/cm in the film, depending on E_P and decaying within some µs due to heat diffusion.

For an estimation of the critical temperature gradient we use $S \simeq 10^{-9}$ erg/(cm K) ($T \simeq T_c/2$) obtained from a calculation of vortex transport entropy at low fields $B \ll Bc_2$ and temperatures by Stephen

[10], a length $L=10^{-3}$ cm of flux lines penetrating the film at some small angle with respect to film surface, and a hopping length corresponding to the distance between layers of reduced order parameter. Intrinsic pinning by these layers has been suggested [11]. We then find $\nabla T_{\mathrm{crit}} \simeq 10^6$ K/cm for a typical activation energy $T_a \sim 1000$ K. We suggest therefore that flux motion in our experiments at low values of E_P is governed by TAFF. At larger gradients ∇T achievable with our laser technique, flux creep and flux flow become probably dominating.

For a discussion of experimental results we write eq. (3) in the form

$$\ln(U_N/E_P) = \ln G - (T_a/T), \quad (5)$$

with $[G=2Bl^2\nu_0 WASL/(cdkT)$ and W the width between electrical contacts. For small values of E_P and fixed T_I, In G may assumed to be constant. Then we find from the slope of ln (U_N/E_P) versus $1/T$ the activation energy $T_a(T_I)$, see fig. 3.

We find the interesting result that T_a is different for each value of T_I and increases with increasing T_I. We interpret this result as an indication for a distribution of activation energies: at small T_I only loosely bound flux can hop due to thermal activation and a correspondingly low activation energy is obtained from the measurement. At high temperatures strongly bound flux is also depinned and contributes to the Nernst signal.

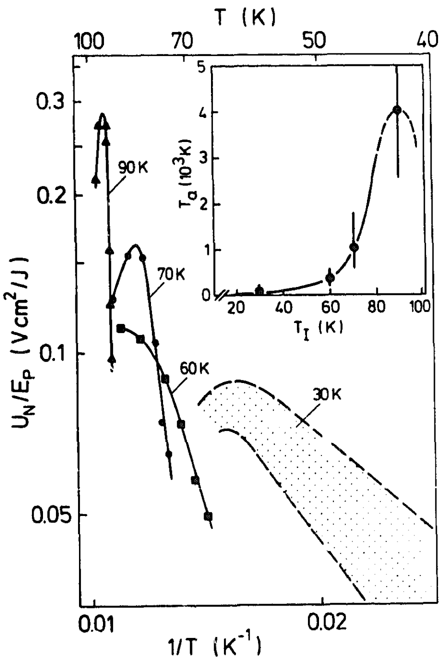

Fig. 3. Normalized Nernst voltage U_N/E_P vs. film temperature T, for various initial temperatures T_I. Inset: activation energies T_a deduced at different T_I.

This observation suggests a description of experimental results by a sum

$$U_N = E_P \sum_i G_i \exp(-T_{a_i}/T). \quad (6)$$

Values for G_i, T_{a_i} can be estimated from the plot of fig. 3. For a first description $i=1, 2$, and values $T_{a_1} \simeq 50$ K, $G_1 \simeq 0.2$ V cm^2/J, $T_{a_2} \simeq 1000$ K, $G_2 \simeq 2\times 10^4$ V cm^2/J associated with the Nernst signal at low and at high temperatures, respectively, are estimated from fig. 3 (measurements $T_I = 30$ K, $T_I = 70$ K). The different values of G_i probably are mainly due to different n_i, $\sum_i n_i \phi_0 = B$, where n_i is an average density of flux tubes activated with activation energy T_{a_i}. From $G_2 \gg G_1$ we conclude that most flux is pinned by the mechanism associated with the activation energy $T_{a_2} \simeq 1000$ K. The full line in fig. 4, where the Nernst voltage at constant E_P (i.e. ~constant ∇T) is shown versus T, is obtained with the values T_{a_i}, G_i given above, and is in overall agreement with the experiment. As G_i and T_{a_i} are taken constant (in fact, $G \propto \nu_0(T)S(T)$ must go to zero near T_c) the decrease of U_N near T_c cannot be reproduced.

The transport entropy S of flux tubes may be estimated from a combined measurement of the Nernst

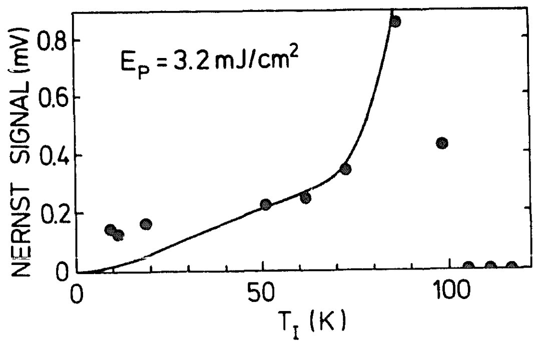

Fig. 4. Nernst signal at constant E_P, in dependence of initial sample temperature T_I (points). Full curve: theoretical description $U_N(T)$ assuming two pinning mechanisms with a low and a high activation energy, respectively (see text). The discrepancy at low T is due to $T > T_I$ by 20–30 K because of small specific heat of the film at low temperatures.

field and the resistivity [2], assuming that the resistivity is purely due to flux motion. Values for S of the same order of magnitude as obtained by Zeh et al. [2] are obtained near T_c. The assumption that ρ is related to flux motion has, however, been questioned in several works [12,13].

In conclusion we have shown that the Nernst effect can be used to investigate the dynamics of magnetic field flux in high-T_c superconductors. The Nernst effect clearly demonstrates flux motion. With our method of generating the temperature gradient by pulsed laser heating, large driving forces can be produced. In combination with a theoretical model, the activation energy T_a has been deduced from experiment, assuming $\nabla T/\nabla T_{crit} < 1$ and flux motion dominated by thermal activated flux flow, similar to the regime of TAFF in transport current measurements.

Our method allows, in addition to time resolution, also for local resolution. Measurements to investigate T_a with respect to film surface coordinates are in progress and may be of interest for technical applications.

Acknowledgement

Valuable discussion with P.H. Kes and P. Esquinazi is gratefully acknowledged. The work was supported by the European Community (Science Program) and by the Bundesministerium für Forschung und Technologie.

References

[1] H. Lengfellner, A. Schnellbögl, J. Betz, W. Prettl and K.F. Renk, Phys. Rev. B 42 (1990) 6264.
[2] M. Zeh, H.-C. Ri, F. Kober, R.P. Huebener, A.V. Ustinov, J. Mannhart, R. Gross and A. Gupta, Phys. Rev. Lett. 26, 3195.
[3] T.T.M. Palstra, B. Batlogg, L.F. Schneemeyer and J.V. Waszczak, Phys. Rev. Lett. 64 (1990) 3090.
[4] R.P. Huebener and A. Seher, Phys. Rev. 181 (1969) 701.
[5] B.D. Josephson, Phys. Lett. 16 (1965) 242.
[6] E.H. Brandt, Int. Conf. on Transport Properties of Superconductivity (April 29–May 4, 1990, Rio de Janeiro, Brazil); ibid. Z. Phys. B 80 (1990) 167.
[7] R.P. Huebener, Magnetic Flux Structures in Superconductors, Springer Series in Solid-State Sciences 6, eds. M. Cardona, P. Fulde and H.-J. Queisser, Berlin (1979).
[8] P.W. Anderson, Phys. Rev. Lett. 9 (1962) 309.
[9] P.H. Kes, J. Aarts, J. van den Berg, C.J. van der Beek and J.A. Mydosh, Supercond. Sci. Technol. 1 (1989) 242.
[10] M.J. Stephen, Phys. Rev. Lett. 16 (1966) 801.
[11] B. Roas, L. Schultz and G. Saemann-Ischenko, Phys. Rev. Lett. 64 (1990) 479.
[12] D.H. Kim, K.E. Gray, R.T. Kampwirth and D.M. McKay, Phys. Rev. B 42 (1990) 6249.
[13] K.C. Woo, K.E. Gray, R.T. Kampwirth, J.H. Kang, S.J. Stein, R. East and D.M. McKay, Phys. Rev. Lett. 63 (1989) 1877.