§36. Quantun Nernst Effect

Nakamura, H.,
Hatano, N. (Univ. of Tokyo),
Shirasaki, R. (Yokohama Nat'l Univ.)

We study the Nernst effect in the regime of the ballistic conduction. Using a simple argument based on edge currents, we predict that, when the chemical potential is located between a pair of Landau levels, (i) the Nernst coefficient is strongly suppressed and (ii) the thermal conductance is quantized with $2(\pi k)^2T/3h$.

The Nernst effect in a bar of conductor is the generation of a voltage difference in the y direction under a magnetic field in the z direction and a temperature bias in the x direction. Each of the left and right ends of the conductor is attached to a heat bath with a different temperature, $T+$ on the left and $T-$ on the right. An electric insulator is inserted in between the conductor and each heat bath, so that only the heat transfer takes place at both ends. A constant magnetic field B is applied in the z direction. Then the Nernst voltage VN is generated in the y direction.

Our basic idea is illustrated in Fig. 1. Because there is no input or output electric current, an edge current circulates around the Hall bar when the chemical potential is in between neighboring Landau levels. The edge current along the left end of the bar is in contact with the heat bath with the temperature $T+$ and equilibrated to the Fermi distribution $f(T+, \mu+)$ while running from the corner C4 to the corner C1. The edge current along the upper edge runs ballistically, maintaining the Fermi distribution $f(T+, \mu+)$ all the way from the corner C1 to the corner C2. It then encounters the other heat bath with the temperature $T-$ and equilibrated to the Fermi distribution $f(T-, \mu-)$ while running from the corner C2 to the corner C3. The edge current along the lower edge runs ballistically likewise, maintaining the Fermi distribution $f(T-, \mu-)$ all the way from the corner C3 to the corner C4. The Nernst voltage $V_N = \Delta\mu/e \equiv (\mu+ - \mu-)/e$ is thus generated, where e(< 0) denotes the charge of the electron.

First, the difference in the chemical potential, $\Delta\mu$, is of a higher order of the temperature bias $f¢T$, because the number of the conduction electrons is conserved. The Nernst coefficient $N = \Delta\mu/\Delta T \times L/(W|e|B)$ hence vanishes as a linear response. Second, the heat current I_Q in the x direction is carried ballistically by the edge current along the upper and lower edges. The edge current does not change much when we vary the magnetic field B as long as the chemical potential stays between a pair of neighboring Landau levels. The thermal conductance $G_Q = I_Q/\Delta T$ hence has quantized steps as a function of B.

We demonstrate the above under the confining potential $V(y) = 0$ for $|y| < w/2$ and $V(y) = m\omega_0^2(|y| - |w/2)^2/2$ for $w/2 < |y| < W/2$ with the effective mass $m = 0.067m_0$ with m_0 being the bare electron mass, the sample size $L = 20$ μ m, the potential width $W = 20$ μ m with $w = 16$ μ m, the potential height $V(\pm W/2) = 5.0$eV, and the chemical potential $\mu = 15$meV, or the carrier density $n_s = 4.24 \times 10^{15}$m^{-2}. Numerical calculation yields $f(T-, \mu-)$ the Nernst coefficient and the thermal conductance as in Fig. 2. We see that our predictions are indeed realized at low temperatures. We also note that the Nernst coefficient is negative in the present case.

The precise forms of the peaks and the risers of the steps in Fig. 2 may be different from the reality. This is because our argument using the edge currents is not applicable when the chemical potential coincides with a Landau level, namely when $\mu = (n+1/2)(h/2\pi)\omega_c$, or $1/B = (n + 1/2)(h/2\pi)|e|/m\mu$. There the heat current is carried by bulk states as well as the edge states. We then have to take account of impurities and possibly electron interactions.

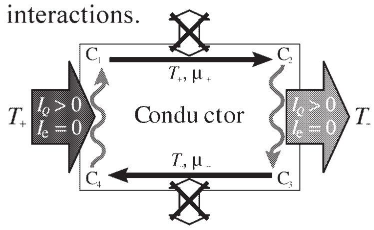

Fig. 1: A schematic view of the dynamics of electrons in a Hall bar under the setup for the Nernst effect.

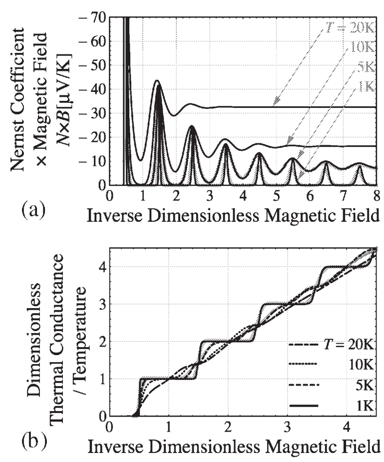

Fig. 2: Scaling plots of (a) the Nernst coefficient against the inverse magnetic field, and (b) the thermal conductance against the inverse magnetic field, at $T = 1$, 5, 10 and 20K for 1T<B<20T.

References

[1] Nakamura, H., Hatano, N., Shirasaki, R.: Solid State Comm., 135 (2005)510.
[2] Shirasaki, R., Nakamura, H., Hatano, N.: e-Journal of Surface Science and Nanotechnology, 3, (2005) 518.