Acta Physica Hungarica 62 /1/, pp. 43-46 /1987/

THERMODYNAMIC CROSS EFFECTS IN TYPE-II SUPERCONDUCTORS

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Investigation of the galvanomagnetic and thermomagnetic effects in superconductors has a special role with respect to the case of normal conductors if these investigations are made in mixed state, because in this case only the normal electrons from the magnetic vortices take part in the effect. Their concentration is smaller than the concentration of the conduction electrons, so the effect taking place is bigger, and depends strongly on the pinning forces. This allows to get a lot of information from this measurement type.

Galvanomagnetic effects

a./ Transversal effects

- Isothermal Hall effect

  The onset of the potential gradient in direction perpendicular to the external electric current /$I_{ee} = I_x$/ and magnetic field /$B=B_z$/, with the boundary conditions $J_{el,y}=0$ and grad $T=0$, in the case if the external magnetic field is greater than the lower critical magnetic field H_{c1}.

- Adiabatic Hall effect

  Similar to the former one and the boundary conditions will be:

$$\frac{\partial T}{\partial x} = 0 \qquad \text{and} \quad J_{s,x} = 0$$

- Ettingshausen effect

  The onset of the temperature gradient perpendicular to the direction of external magnetic field B_z, and electric current J_x, with the boundary conditions:

$$J_{el,y} = 0, \quad J_{s,y} = 0 \quad \text{and} \quad \frac{\partial T}{\partial x} = 0$$

b./ Longitudinal effects

- Isothermal electric resistivity
- Adiabatic electric resistivity

  In the case of superconductors the value of these effects is zero.

Thermomagnetic effects

a./ Transversal effects

- Righi -Leduc effect

  The onset of the temperature gradient perpendicular to the x direction temperature gradient and Z direction magnetic field, with the boundary conditions:

  $$J_{el} = 0 \text{ and } J_{s,y} = 0$$

  /perhaps the magnetic field must be higher than H_{cl}/

- Isothermal Nernst effect

  In the case of the applied magnetic field $B=B_Z$ and heat current $J_s=J_{s,x}$ the onset of the potential gradient, with the boundary conditions:

  $$J_{el} = 0 \qquad \text{and} \qquad \frac{\partial T}{\partial y} = 0$$

- Adiabatic Nernst effect

  Similar to the former, but with the boundary condition $J_{s,y}=0$ instead of the 0 temperature gradient

b./ Longitudinal effects

- Isothermal thermal conductivity
- Adiabatic thermal conductivity

  In the case of boundary conditions

  $$J_{el}=0 \text{ and } \frac{\partial T}{\partial y}=0 \text{ or } J_{s,y} = 0$$

  The coefficient of thermal conductivity

  $$\lambda = - \frac{T\, J_{s,x}}{\text{grad}_x T}$$

  has a strong magnetic field dependence, because the Cooper-pairs do not take part in heat conduction, only the normal electrons appearing in magnetic vortices. At the same time the concentration of the vortices depends on the value of the magnetic field

- Isothermal Ettingshausen-Nernst effect

  Appearence of the potential gradient in the x direction due to the applied magnetic field $B=B_x$ and temperature gradient $\text{grad}_x T$, with boundary conditions

  $$J_{el} = 0 \text{ and } \frac{\partial T}{\partial y} = 0$$

- Adiabatic Ettingshausen-Nernst effect

  Similar to the former but in the boundary conditions we will have $J_{s,y} = 0$

Because of the Onsager reciprocity relations there exists the Bridgman-type equation

$$T\, Q_i^t = \lambda_i \Phi^t$$

/Q_i^t is the isothermal Nernst coefficient, λ_i the isothermal coefficient of thermal conductivity and Φ^t the Ettingshausen coefficient/.

Experimental results

We have made the experimental investigation of Nernst effect in superconducting samples of Pb-Sn with content of Sn 50 atomic percent. The effect takes place only if $H \gg H_{c1}$ because in the Meissner state the electric field cannot appear in superconducting sample. We have used cylindrical samples with a diameter of 4 mm and a length of 50 mm. They were prepared by quenching from liquid state to the nitrogen temperatures [2] .

The system position of measurement is shown in the Fig. 1. . The measurements allow a very precise determination of the lower critical magnetic field H_{c1} (see Fig. 2.) [3] , because the onset of the potential gradient is very sharp when the magnetic field penetrates the sample. The results provided by this method are in good agreement with the values of H_{c1} determined by magnetisation measurements [4] .

The appearence of the effect is similar to the appearence of Hall effect. If we have the magnetic vortices in our sample, they feel the effective thermodynamic force $-(\Phi_0 S'/B)$ grad T due to the heat current /Φ_0 is the flux quantum, and S' is the entropy density/, and the vortices can move from the hotter place to the colder if this force is bigger than the pinning force. At the hot end of the sample the vortex density is higher, here the vortex lines permanently move into the sample, and at the cold end they permanently leave it. The Lorentz force acts on the normal electrons in moving vortices resulting in vortex density gradient in y direction, and E_y potential gradient. The effect disappears at H_{c2}, because with the magnetic vortices disappearing the moving electrons disappear too. The hysteresis we have found is the result of the pinning forces bounding a part from vortices. The value of the effect has strong pinning force dependence. If the pinning forces are strong enough the effect will disappear. In this case the thermodynamic force will be less than the pinning forces. If the vortices are bound the flow disappears. If we put the sample into the cryostat immediately after quenching it cannot recrystallise. In the other case strong pinning centres are formed and the effect diappears. The magnetisation curves show these phenomena very well.

References

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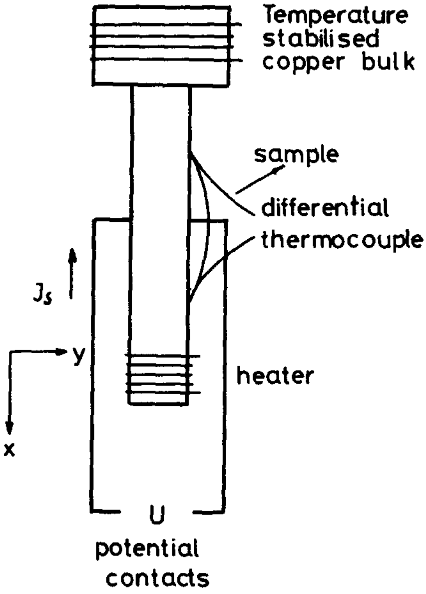

Fig.1 The system of measurement

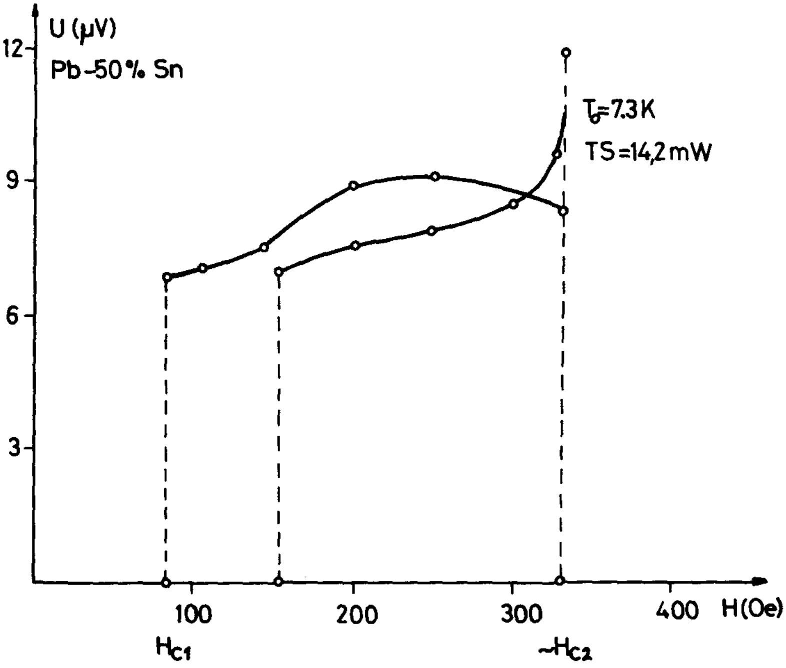

Fig.2. The Nernst effect