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ANISOTROPIC THERMAL CONDUCTIVITY IN A DIRTY TYPE II SUPERCONDUCTOR

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Résumé.- Des mesures de conductibilité thermique ont été effectuées sur un alliage Pb - 21 at.% In dans l'état mixte, avec un gradient de température parallèle aussi bien que perpendiculaire à l'induction magnétique. Les résultats sont comparés avec des calculs de Watts - Tobin et Imai.

Abstract.- Thermal conductivity measurements have been carried out on a Pb - 21 at.% In alloy in the mixed state, both with a temperature gradient parallel and perpendicular to the magnetic induction. The results are compared with calculations by Watts - Tobin and Imai.

For dirty type II superconductors transport coefficients can be calculated, using a formalism as described by Pesch, Watts - Tobin and Kramer (PWTK) /1/. In this way they determined the electronic contribution to the thermal conductivity throughout the whole mixed state regime. Both cases of a temperature gradient parallel and perpendicular to the magnetic induction have been studied, by PWTK /1/ and Imai and Watts - Tobin /2/, respectively. If the mean free path of the electrons ℓ_{ep} for inelastic scattering by phonons is much larger than the scale of the mixed state structure, the electronic conductivity appeared to be anisotropic.

We have measured the thermal conductivity of a cylindrical Pb - 21 at.% In sample in both situations at several temperatures. Some relevant parameters for this alloy are $\kappa = 3.8 \pm 0.1$, the dirt-parameter $\alpha = 0.882\ \xi_0/\ell_e = 17$, $T_c = 6.90$ K and $\Delta(0/k_BT_c = 2.18$.

In this paper we use the subscripts "e" and "p" to denote the electronic and phonon contributions, $//$ and $\perp$ refer to the parallel and perpendicular situations. The superscripts "s" and "n" are used for quantities in the Meissner and normal states, respectively.

For the thermal conductivity measurements a conventional stationary flow method was used /3/. The normal and Meissner state conductivities were measured between 1.1 K and 9 K. We separated /4,5/ the electron and phonon contributions, using the residual resistivity ρ_0, the Wiedemann-Franz law $\lambda_e^n = L_0\ T\ \rho_0^{-1}$ and the BRT formula /6/ for $\Delta(0)/k_BT_c = 2.18$. In parallel field we also measured the magnetization of the sample, using a flux-transformer and a HP model 3529 A magnetometer probe. In this way we obtained the thermal conductivity as a function of magnetic induction, $\lambda_{//}(B)$. In order to determine $\lambda_\perp(B)$ we calculated the magnetization curve in perpendicular field from the parallel one /4/.

Before we compare our results with the theotical ones for $\kappa = 4$, we note :

i) As λ_p is of the same order as λ_e, and for the lower B values even much larger, it appeared to be difficult to separate these two contributions in the mixed state. Therefore we concentrated on the difference $\lambda_{//}(B) - \lambda_\perp(B)$ of the total conductivities.

ii) The theoretical calculations are valid only for BCS - superconductors. The results could not be generalized to the strong-coupling case in any direct way. However, as the theoretical results did not have much structure as a function of B, we had recourse to a simple scaling procedure. We assumed $(\lambda_e\ (B/H_{c2}) - \lambda_e^s)\ /\ (\lambda_e^n - \lambda_e^s)$ to be independent of $\Delta(0)/k_BT_c$ and replaced to BCS-value of λ_e^s/λ_e^n as given by BRT /6/ by the value corresponding to $\Delta(0)/k_BT_c = 2.18$.

iii) We estimated the quantity ℓ_{ep} using a formula given by Klemens /7/

$$\frac{\lambda_{pe}^n}{\lambda_{ep}^n} = \frac{313}{n_a^{4/3}} \left(\frac{T}{\theta_D}\right)^4$$

in which λ_{pe}^n is the conductivity of phonons, only scattered by electrons and λ_{ep}^n the conductivity of the electrons, only scattered by phonons. n_a is the number of electrons per atom and θ_D the Debye temperature. Combined with $\lambda_{ep}^n\ /\ \lambda_e^n = \ell_{ep}/\ell_e$ as given by the normal state data, this yielded $\ell_{ep} \approx 0.4\ T^{-3}$ cm. As the coherence length ξ is of the order of a few hundered Angstrom at the temperature considered, we should expect an anisotropy as predicted by the theory.

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In figure 1 we compare the theoretical $(\lambda_{e//} - \lambda_{e\perp})/\lambda_e^n$ curve with the experimental $(\lambda_{//} - \lambda_{\perp})/\lambda_e^n$. The experimental results show two distinct features :

i) Qualitative agreement with the theory is found for $B \gtrsim 0.2\ H_{c2}$.

ii) For lower B values a large peak shows up, which is not predicted by the theory. Its magnitude is too large compared to $\lambda_e\ (B)/\lambda_e^n$ to be due to a deviation from the theory. We think it rather indicates an anisotropy of the phonon conductivity up to 10 % of λ_p^s.

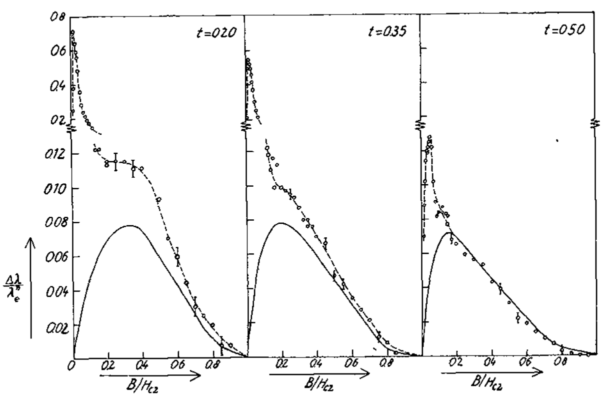

Fig. 1 : Comparison of the theoretical $(\lambda_{e//} - \lambda_{e\perp})/\lambda_e^n$ (continuous curves) with the experimental $(\lambda_{//} - \lambda_{\perp})/\lambda_e^n\ (0)$ for the reduced temperatures t = 0.20, 0.35, 0.50, (----------: smoothed experimental data)

There are some simple arguments supporting this view. The wave-length of thermal phonons $\Lambda_p \sim 5 \times 10^{-6}\ T^{-1}$ cm is of the same order or smaller than ξ which seems to be a necessary condition for an anisotropy to occur at all. For values of $B \lesssim 0.1\ H_{c2}$, but not too small, the mean free path of thermal phonons ℓ_p is much larger than the lattice parameter of the vortices a_o. Therefore the vortices may be considered as randomly distributed. Phonons in the perpendicular direction see the vortices as a thermal resistence in series with the Meissner region, whereas for phonons in the parallel direction these regions are more like parallel conductors. When estimating the ratio of the respective mean free paths $\ell_{p//}/\ell_{p\perp}$, we find a fast increase with B increasing from zero. However, as the vortices get closer and start to overlap, this model breaks down and the anisotropy vanishes for higher B, in agreement with experiment.

A rigorous calculation which should take into account the detailed structure of the vortex lattice, could perhaps give a more quantitative answer to this problem. However, as the above qualitative arguments support the idea that the superimposed peak can be attributed to the phonons, we may conclude that our measurements are in reasonable agreement with the theoretical predictions for the anisotropy in the electronic conductivity.

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