Strong Coupling Effects in the Temperature Dependence of the Flux-Flow Resistance Near $H_{c2}$

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A refined experimental technique is applied to measure the flux-flow resistance of the strong coupling alloys Pb$_{0.9}$In$_{0.1}$, Pb$_{0.8}$In$_{0.2}$ and Pb$_{0.7}$In$_{0.3}$ and to get the deviations from weak coupling theories. In order to test a theory by Imai devised for arbitrary coupling strengths static quantities entering the flux-flow resistance formulas are calculated using extrapolated tunnel spectra.

1. Introduction

There has been much experimental and theoretical interest into the flux-flow resistivity of homogeneous type II superconductors in the last years, especially near the upper critical field. Caroli, Maki [1] derived for the normalized differential resistivity $\alpha$ the formula:

$$\alpha = \frac{d\rho_f}{dH} \frac{H_{c2}}{\rho_n} = \frac{4\kappa_2(0)}{1.16[2\kappa_2(t) - 1]}$$

(1.1)

with $\rho_n$ the normal state resistivity and $\kappa_2$ the Ginzburg-Landau parameter as introduced by [2]. Lateron, Thompson [3] showed that formula (1.1) is only valid in the strong pair breaking limit because [1] neglected anomalous contributions which become important near $H_{c2}$ for materials with weak pair breaking. Their formula reads:

$$\alpha = \frac{4\kappa_2(0)}{1.16[2\kappa_2(t) - 1]} \left[ 2 + \rho \Psi'' \left( \frac{1}{2} + \rho \right) \right]$$

(1.2)

with $\Psi$ the digamma function and

$$\rho(t) = \frac{2eDH_{c2}(t)}{4\pi T}$$

here $D$ is the diffusion constant $D = \frac{1}{2} v_f l$, $v_f$ the Fermi velocity, $l$ the mean free path for impurity scattering. (1.2) differs from (1.1) by a factor of 2 for $t = T/T_c = 1$ and approaches (1.1) as $t \rightarrow 0$. Formula (2) is valid only in a small region near $H_{c2}(T)$ which shrinks to zero at $T \rightarrow T_c$:

$$H_{c2}(t) - H \ll H_{c2}(t)/H_{c2}(0).$$

(1.3)

For smaller values of the magnetic field $H$ the flux-flow resistivity rapidly approaches the result of [1] as [4] showed. Formulas (1.1) and (1.2) both refer to the weak coupling case ($\lambda_{\text{McMillan}} \ll 1$). For arbitrary values of $\lambda$ Imai [5] obtained, removing some inconsistencies in the calculation of the fluctuation propagator by [6]:

$$\alpha = \frac{4\kappa_2(0)}{1.16[2\kappa_2(t) - 1]} \left[ 1 + \frac{\tilde{\rho}_0}{\tilde{\rho}} \frac{\Psi'' \left( \frac{1}{2} + \tilde{\rho} \right)}{\Psi'' \left( \frac{1}{2} + \frac{1}{\tilde{\rho}} \right)} \right]$$

(1.4)

Here strong coupling corrections arise in the "static" prefactor, which describes the relationship between the static magnetization and the magnetic field and in a renormalization of the diffusion constant by the McMillan $\lambda$:

$$D \rightarrow D^* = \frac{D}{1 + \lambda}.$$

Now we have two pair breaking parameters: $\rho$ and the electron phonon scattering time $1/\tau_{\text{phon}}$, which add to the new parameter:

$$\tilde{\rho} = \rho_0 + 1/(\tau_{\text{phon}} 4\pi T), \quad \tilde{\rho}_0 = \rho/(1 + \lambda).$$

(1.5)

This extra pair breaking parameter causes the second factor to coincide with the value of Caroli, Maki both at $t = 0$, and $t = 1$. So at $t = 1$ it differs by a factor of two from Thompson's result. The detailed behaviour
of \( z \) as a function of the reduced temperature \( t \) depends very much on the values of the static magnetization.

Earlier measurements of the flux-flow resistivity give results which are consistent with the predictions of formula (1.1) [7–10]. But later [11] confirmed formula (1.2) by surface impedance measurements for PbIn samples. [12] obtained values which are near the Thompson result for \( t < 0.8 \) but bend downwards at higher temperatures in a flux-flow experiment using improved techniques.

There has still been some scatter in the data of this experiment caused by a non optimized sample holder and temperature regulation and measurement especially at lower temperatures. Therefore we found it worthwhile to improve the precision of the measurements to such a degree that deviations from the values of the Thompson theory can be attributed to strong coupling effects in the PbIn samples with \( \lambda \) values near 1.5 and quantitatively be compared to the theory of [5] which yields formula (1.4). For such a comparison \( \kappa_2 \) as a function of \( t \) has to be known. Measurements of this quantity as reported in literature yield results differing from each other. [13] deduced \( \kappa_2 \) from measurements of the jumps in the surface impedance at \( H_{c2}(T) \) and \( H_{c3}(T) \). [14] measured the slope of the magnetization curve near \( H_{c2} \). These experiments lead to quite different flux-flow curves. Therefore we found it reasonable to evaluate \( \kappa_2(t) \) using the formulas as derived by [15] in the dirty limit.

In Section 2 the experimental refinements leading to a significant reduction in the scatter of the data are described in detail. Section 3 is devoted to a description of the methods used for the evaluation of the quantities entering the formula (1.4) for the flux-flow resistivity. In Section 4 we compare the results of Sections 2 and 3 to Imai's theory.

2. Improvements in the Experiment

In order to discuss the improvements in the present experimental arrangement we briefly describe the equipment used to obtain the results described in [12].

To achieve a constant temperature over the whole probe a sample mounting has been constructed which is quite different from that usually used in flux-flow experiments. The schematic arrangement is shown in Figure 1.

Rather than being placed into a helium bath, the sample is put into vacuum and connected to the bath by a thermal resistance. The sample is attached to a copper-block and electrically isolated by a Deltabond layer. A small carbon resistor directly fixed to the sample measures its temperature. An important advantage of this device is the possibility to monitor the temperature continuously and independent from the power input to the sample.

Temperature regulation has been achieved by means of a heater controlled by an electronic circuit.

To obtain a direct digital readout of the differential flux-flow resistance \( R_f = dV/dI \), we make use of a low frequency current modulation technique. A small a.c.-current \( I_{ac} \) is superposed to the d.c.-current \( I_{dc} \), \( I_{ac} \) being always kept lower by a factor of \( 10^{-2} \)-\( 10^{-4} \). We made sure that \( I_{ac} \) does not influence the critical current or \( R_f \).

A certain amount of scatter in our data led us to make the following improvements:

In order to increase the stability of the temperature control circuit both the thermal resistance of the copper block to the helium bath and its heat capacity have been increased. In addition we used a commercial Allen-Bradley resistor for thermometry instead of the self-built carbon resistor of the previous experiments. The A-B resistor was grinded down to get a flat surface and glued onto the sample with GE-varnish 7031. The improved temperature control made it possible to use the original carbon-metal contacts of the A-B resistor in order to avoid the mechanical and electrical degradation sometimes occurring in our former thermometers. In order to eliminate thermo-voltages we changed the temperature control from d.c. to a.c., by employing an A-C-Bridge with a Lock-In Amplifier as null-detector.

These refinements allow us to keep the temperature constant better than 1 mK. So we obtain very accurate flux-flow resistance dates even near \( H_{c2} \) and for rather high reduced temperatures. This is demonstrated by a significant reduction in the scatter of dates as compared to the previous experiments.