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Specific Heat and Thermal Conductivity of Superconducting UBe_{13} and UPt_3 at Very Low Temperatures

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Non-exponential temperature dependences of various physical properties in the superconducting state of UBe_{13} and UPt_3 have been put forward as evidence for unconventional superconductivity in these materials. We report new experimental results for the specific heat c_p and the thermal conductivity λ of UBe_{13} and UPt_3 down to temperatures well below 0.1 K. In none of these measurements can an exponential temperature dependence be recognized. In some aspects, our data differ from those that were previously published. This indicates that sample purity and imperfection may be of importance.

Soon after the discovery of superconductivity in UBe_{13} [1] and UPt_3 [2] it was suggested that both the mechanism leading to superconductivity and the characteristics of the superconducting state were most likely of unconventional nature [3]. Especially the latter was proposed, because various thermal and transport properties determined experimentally did not show the general behaviour that is expected from BCS theory. This theory assumes that the superconducting transition is accompanied by the formation of a gap in the electronic energy excitation spectrum which is nonzero over the entire Fermi surface. This then results in exponential temperature dependences of many physical properties at temperatures below the superconducting transition at T_c.

It is a characteristics of unconventional superconducting states, such as those established for the superfluid states of liquid ^3He, that the above mentioned gap formation is altered in the sense that it is intrinsically zero on distinct parts of the Fermi surface. The location of these gap zeroes depends on the symmetry of the order parameter of the adopted superconducting state. In this case, the temperature dependences of physical properties in the superconducting state that are governed by electronic excitations are no longer of exponential character. Different arrangements of gap zeroes are related with different energy dependences of the electronic density of states N(E) in the region, where $E \rightarrow 0$ K. The most simple arguments usually lead to power-law behaviour in these temperature dependences. It has been recognized, however, that more thorough discussions of possible influences may alter these simple predictions. As one example for this latter statement we mention a recent study of the temperature dependence of the specific heat of superconducting UBe_{13} at temperatures well below T_c, where evidence for the influence of impurity scattering on $c_p(T)$ as T approaches 0 K was found [4].

Here we present new results of measurements of the thermal conductivity λ of the same sample of UBe_{13} that was used in the mentioned $c_p(T)$ study down to temperatures of about 50 mK. Our results below 0.2 K are shown in fig. 1. These $\lambda(T)$ values are similar in magnitude to other previously published data [5] but they also differ in the sense that the temperature dependence below 0.1 K is not the same as found in previous investigations.

While Jaccard and Flouquet [5] found an approximately linear temperature dependence of λ below 100 mK as indicated by the broken line in fig. 1,

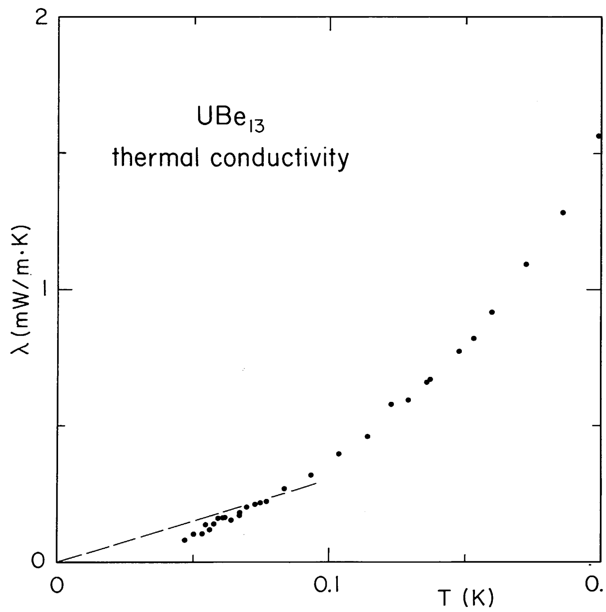

Fig. 1. Thermal conductivity of superconducting UBe_{13} below 0.2 K. The broken line is a fit to previous data as given in ref. 5.

we find in the same temperature range a behaviour that is more close to a T^2 variation. We agree, however, with Jaccard and Flouquet that a simple power law in T does not describe $\lambda(T)$ over an extended range of temperatures. Nevertheless, this comparison again demonstrates that differences in sample quality may be decisive for the behaviour of physical properties of these superconductors for $T/T_c \ll 1$, as was already concluded for UBe_{13} in ref. 4 on the basis of different results for $c_p(T)$ in this temperature range.

With this information about the superconducting state of UBe_{13} we felt it to be worthwhile to undertake an analogous investigation of UPt_3. Already previous work from different sources [6,7] showed considerable differences in $c_p(T)$ of UPt_3 below T_c but fairly good quantitative agreement for $\lambda(T)$. In both investigations that were reported, $c_p(T)$ contains a considerably large term which varies linearly with temperature, but these two terms seem to differ by a factor of 2 for different samples from different sources. Our sample was cut from a piece where the adjacent part was successfully used for de Haas-van Alphen studies and therefore we expect this sample to be of very high quality.

Our values for $c_p(T)$, which were obtained down to temperatures of about 70 mK, are shown in fig. 2 for T < 0.3 K and plotted as c_p/T versus T. The broken line is a conventional extrapolation to T = 0 K and is compatible with a vanishing linear-in-T contribution to c_p in that limit. This is clearly different from what was obtained in previous investigations [6,7] where $c_p(T)$ could be expressed as a sum of two terms $\gamma T + \beta T^2$ and γ turned out to exceed a value of 0.1 J/mole K^2. The prefactor of the T^2 term in our case is β = 1.975 J/mole K^3, as compared to 1.25 J/mole K^3 obtained by Sulpice and co-workers [7].

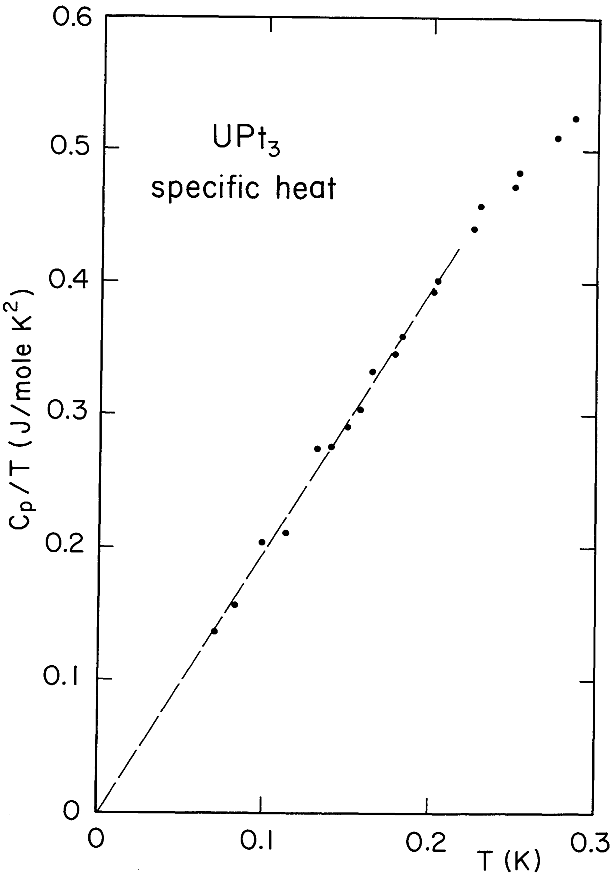

Fig. 2. Specific heat of superconducting UPt_3 below 0.3 K. The broken line is a guide to the eye.

From our experience with UBe_{13}, however, we hesitate to claim that this kind of extrapolation is valid for $T \ll T_c$. Because T_c of UPt_3 is only about half of that of UBe_{13} we have not yet reached the really low-temperature limit in our experiments with UPt_3. Nevertheless we are confident in claiming that an improvement of sample quality leads to a reduction of the c_p values of superconducting UPt_3 as $T \rightarrow 0$ K, in agreement with expectations for the behaviour of unconventional superconductors.

Finally we display our results for $\lambda(T)$ of UPt_3 at temperatures below 0.2 K in fig. 3. For comparison we also show the broken line that fits the data of Sulpice and co-workers [7] very well. It

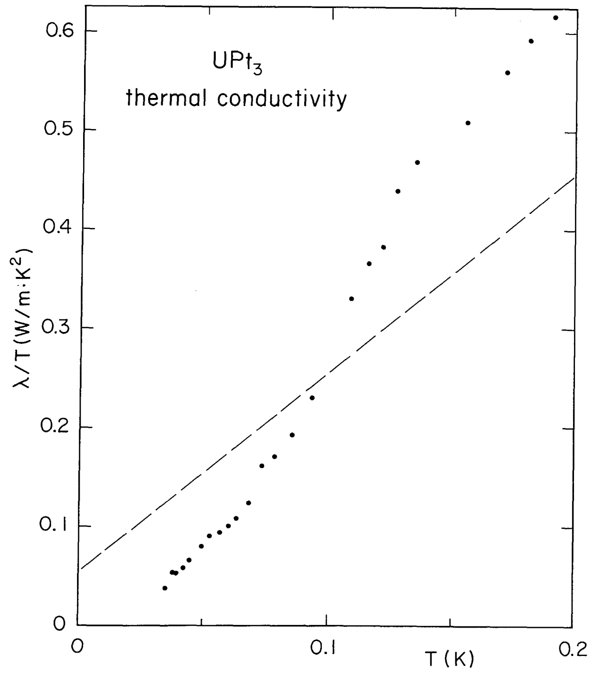

Fig. 3. Thermal conductivity of superconducting UPt_3 below 0.2 K. The broken line represents data of ref. 7.

is apparent that our $\lambda(T)$ values are higher above 0.1 K but clearly exhibit a different temperature dependence which leads to much lower values below 0.1 K. This is again compatible with the assumption that our sample is of better quality than those used in previous investigations, as also indicated by our $c_p(T)$ result. We cannot fit our $\lambda(T)$ data with a simple power law over an extended temperature range, but it is clear that they include a term that varies more strongly than T^2.

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