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Title
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Permalink
https://escholarship.org/uc/item/7t46563h

Journal
Physica B Condensed Matter, 284(PART I)

ISSN
0921-4526

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Publication Date
2000-07-01

DOI
10.1016/s0921-4526(99)02132-8

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Physica B 284–288 (2000) 529–530

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Low-temperature specific heat of the heavy electron superconductor $U_{1-x}Th_xBe_{13}$ ($x = 0$, 0.033) in external magnetic fields

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Abstract

We report on results of low-temperature specific-heat measurements of the unconventional superconductors UBe_{13} and $U_{0.9669}Th_{0.0331}Be_{13}$ in external magnetic fields up to 7 T. For $T \ll T_c$, or, respectively, T_{c2} for the thoriated sample, the magnetic field-induced contribution to $C_p(T, B)$ varies linearly with temperature, which is consistent with the temperature dependence of the specific heat due to the flow of supercurrent around the vortices. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Heavy fermions; Specific heat in magnetic fields; UBe_{13}

The phase diagram of the heavy electron superconductor UBe_{13} upon doping with Thorium is rather complex and interesting. In the range $0.018 < x < 0.045$, two consecutive phase transitions at T_{c1} and T_{c2} are observed [1]. This has been taken as a strong evidence for unconventional superconductivity in this system. The specific heat of UBe_{13}, varying as T^3 well below T_c, is yet another indicator of an unconventional order parameter, with point-nodes in this case [2]. The specific heat C_p of these heavy electron compounds is, at temperatures well below T_c, dominated by a large electronic contribution. Therefore, measurements of the specific heat may directly serve as a tool to investigate the features of the electron density of states (EDOS).

In the mixed state of a superconductor, the superflow circulating around a vortex with the velocity $v_s = \hbar/2m(\nabla\phi - e\mathbf{A})$ causes a Doppler shift of the energy. This results, in the presence of gap-nodes, in a non-zero DOS at zero energy given by [3]:

$$N(0) \sim N_F\left(\frac{B}{B_{c2}}\right)^{1-D/2}, \tag{1}$$

where N_F is the DOS at the Fermi energy E_F in the normal state and D the dimensionality of the gap-nodes. This leads to an additional linear-in-T term to $C_p(T)$ at $T \ll T_c$ of the form

$$\frac{C_p}{T} \sim \left(\frac{B}{B_{c2}}\right)^{1-D/2}. \tag{2}$$

We measured the specific heat $C_p(T, B)$ on small pieces of high-quality polycristalline $U_{1-x}Th_xBe_{13}$ ($x = 0$, 0.033) using a conventional thermal-relaxation calorimeter. Special care was taken to calibrate the thermometer attached to the sample platform in high external magnetic fields. With this setup we are able to perform measurements of the specific heat either as a function of the applied field at constant temperature or vice versa. All the experiments have been made in a dilution refrigerator in the center of a superconducting magnet. The specific heat of the platform has been measured in a separate experiment and was in both cases only a few

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PII: S0921-4526(99)02132-8

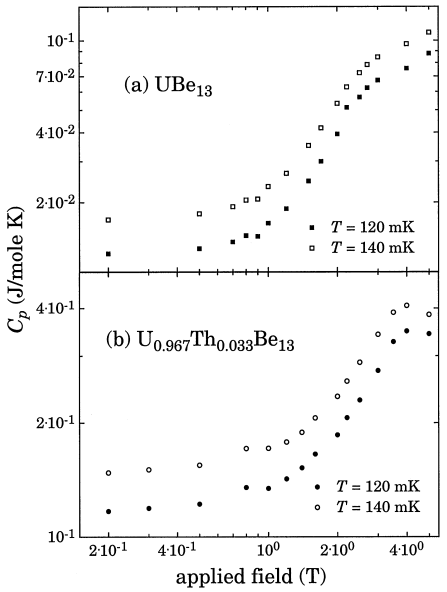

Fig. 1. Specific heat versus applied magnetic field at constant temperatures for $U_{1-x}Th_xBe_{13}$ for $x = 0$ (a) and $x = 0.033$ (b) on log–log scale.

ppm of the total specific heat. The preparation of the samples is described in great detail elsewhere [4].

In Fig. 1, we show the specific heat as a function of applied magnetic field at constant temperatures for both compounds. For small applied fields, the field dependence of the specific heat $C_p(B)$ is rather weak, and becomes much stronger for fields $\mu_0 H > 1$ T. For the binary compound, the slope changes again at $\mu_0 H \approx 3$ T, whereas for the thoriated sample the dramatic change of slope at $\mu_0 H \approx 4$ T is due to approaching B_{c2}.

In Fig. 2, we show the specific heat $C_p(\mu_0 H) - C_p(0)$ as a function of T at constant fields. In agreement with Eq. (2), the contribution to the specific heat due to the current superflow around the vortices is indeed linear in T at low enough temperatures. For both, the pure and the thoriated UBe_{13}, the magnetic-field-induced contribution to the specific heat varies linearly with T, indicated by the solid lines in Fig. 2.

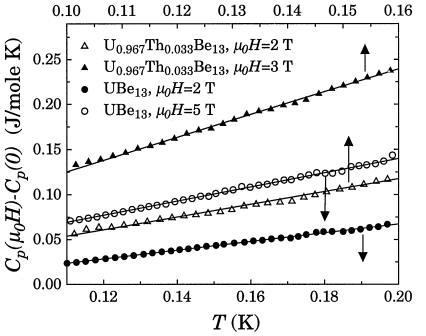

Fig. 2. Magnetic contribution to the specific heat, $C_p(\mu_0 H) - C_p(0)$, versus T for $U_{1-x}Th_xBe_{13}$. Note the different temperature axis for the different Th-concentrations x. The solid lines represent fits of Eq. (2) to the data.

In conclusion we note, that the field-induced excess specific heat in the mixed state of both pure and thoriated UBe_{13}, is linear in T, which is consistent with the theoretically predicted temperature dependence of the specific heat caused by the supercurrent circulating around the vortices.

Acknowledgements

We thank Nippon Steel Corporation for letting us use their magnetic shields, allowing very accurate thermometry in magnetic fields. Part of this research was supported by the Schweizerische Nationalfonds zur Förderung der wissenschaftlichen Forschung.

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