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Low-temperature specific heat of the heavy electron superconductor \( \text{U}_{1-x}\text{Th}_x\text{Be}_{13} (x = 0, 0.033) \) in external magnetic fields

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Abstract

We report on results of low-temperature specific-heat measurements of the unconventional superconductors \( \text{UBe}_{13} \) and \( \text{U}_{0.9669}\text{Th}_{0.0331}\text{Be}_{13} \) in external magnetic fields up to 7 T. For \( T \leq T_c \), or, respectively, \( T_{c2} \) for the thoriated sample, the magnetic field-induced contribution to \( C_T(T, B) \) varies linearly with temperature, which is consistent with the temperature dependence of the specific heat due to the flow of supercurrent around the vortices.

Keywords: Heavy fermions; Specific heat in magnetic fields; \( \text{UBe}_{13} \)

The phase diagram of the heavy electron superconductor \( \text{UBe}_{13} \) 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 \( \text{UBe}_{13} \), 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 \( v_s = \hbar/2m(\nabla \Phi - eA) \) 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]:

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

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

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

We measured the specific heat \( C_p(T, B) \) on small pieces of high-quality polycrystalline \( \text{U}_{1-x}\text{Th}_x\text{Be}_{13} (x = 0, 0.033) \) 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
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.

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.

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References