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Journal

Physical Review B - Condensed Matter and Materials Physics, 63(10)

ISSN

0163-1829

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Publication Date

2001

DOI

10.1103/PhysRevB.63.100505

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Peer reviewed

Scaling properties of the magnetic-field-induced specific heat of superconducting UBe₁₃

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(Received 26 December 2000; published 15 February 2001)

We report on measurements of the low-temperature specific heat $C_p(T, B)$ of the unconventional superconductor UBe₁₃ in magnetic fields up to 7 T. At $B \approx 2$ T, a substantial change in the magnetic-field dependence of the temperature derivative of the magnetic-field induced contribution to the electronic specific heat $C_H(T, B)$, resulting from the flow of supercurrents around the vortices, is observed, suggesting a crossover between two different regions in the superconducting phase diagram of UBe₁₃. For fields $B > 2$ T, $C_H(T, B)$ exhibits a scaling behavior with respect to $TB^{-1/2}$, which provides substantial evidence for the existence of point nodes in the quasiparticle excitation spectrum of the superconductor.

DOI: 10.1103/PhysRevB.63.100505

PACS number(s): 74.70.Tx, 74.25.Bt, 71.27.+a

Ever since the discovery of the heavy-electron superconductor UBe₁₃,¹ both, experimental as well as theoretical efforts have been made to establish or characterize the nature of superconductivity in this compound.^{2,3} Among various other indications, the anomalous behavior of the specific heat at temperatures well below T_c ($C_p \propto T^3$)⁴ or the London penetration depth below T_c ($\Delta \lambda \propto T^2$)⁵ have been interpreted as evidence, that superconductivity in this compound is of unconventional nature. Inspired by these power-law temperature dependencies of various properties, it has been proposed that the superconducting state is an axial⁴⁻⁶ spin-triplet state. However, the definitive identification of the proper symmetry of the superconducting order parameter is still not complete.

The magnetic field induced contribution to the specific heat $C_p(T, B)$ of a superconductor with gap-nodes strongly depends on the topology of these nodes, and therefore measurements of the specific heat in external magnetic fields may directly serve as a tool for investigating the topology of the gap nodes.⁷ In several recent specific heat studies of the high- T_c superconductor YBa₂Cu₃O₇ (YBCO) (Refs. 8–11) and the heavy-electron superconductor UPt₃,¹² the magnetic-field induced contribution to the specific heat has been investigated and found to match the predictions for a superconductor with line-nodes in the quasiparticle excitation spectrum. In this letter, we demonstrate the existence of a crossover at $B \approx 2$ T between two different regions in the phase diagram of UBe₁₃ and we further demonstrate that for $B > 2$ T, the behavior of $C_H(T, B)$ of the heavy-electron superconductor UBe₁₃ as a function of T and B leads to the conclusion, that its superconducting energy gap exhibits point nodes.

In the mixed state of a type-II superconductor, the superflow circulating around a vortex causes a Doppler shift ΔE_D of the energy scale. For small gap values, i.e., at and close to the gap nodes, this shift causes a nonzero density of electronic states (DOES) at zero energy which depends on the

topology of the gap nodes. In the limit $k_B T \ll \Delta E_D$ and $B \ll B_{c2}$, the DOES at zero energy in the case of point nodes, is given by $N(0)/N_F \sim B/B_{c2} \ln(B_{c2}/B)$ for an arbitrary direction of the magnetic field, or $N(0)/N_F \sim B/B_{c2}$, if the field is exactly parallel to the orientation of the nodes, respectively. For line nodes, $N(0)/N_F \sim (B/B_{c2})^{1/2}$, independent of the direction of the magnetic field.¹³ Here N_F is the DOES at the Fermi energy E_F . This leads, in the limit of $T \ll T_c$, to an additional linear-in- T term to C_p of the form⁷

$$\frac{C_H(T, B)}{T} \sim \frac{N(0)}{N_F}. \quad (1)$$

A more general way to analyze the magnetic-field induced specific heat has recently been discussed by Volovik¹⁴ and by Simon and Lee.¹⁵ They showed that the magnetic-field induced contribution to the specific heat $C_H(T, B)$ obeys a scaling behavior, with respect to the scaling parameter $x \sim (T/T_c) \sqrt{B_{c2}/B}$, of the form $C_H(T, B) \sim B^{((3-D)/2)} f(x)$. This scaling may be rewritten as

$$\frac{C_H(T, B)}{T^{2-D} B^{1/2}} \sim F(x), \quad (2)$$

where D denotes the dimension of the nodes, i.e., $D=0$ for point nodes and $D=1$ for line nodes. $F(x)$ is a universal scaling function.^{14,15} According to Eq. (1), its asymptotic behavior for $x \ll 1$ is of the form $F(x) \sim x^{D-1}$. We note that in the case of point nodes an additional term due to the logarithmic term in the DOES, which would invalidate the scaling relation, enters Eq. (2). Nevertheless, it can be shown that in materials with cubic symmetry, this term may well be small enough to not significantly affect the scaling relation given in Eq. (2).¹⁶

In order to test these scaling predictions in connection with an unconventional and strongly type-II heavy-electron superconductor, the specific heat $C_p(T, B)$ of a small piece of polycrystalline UBe₁₃ (~ 50 mg) has been measured in

various temperature ranges between 0.08 and 0.38 K and in external magnetic fields between 0 and 7 T, using a thermal-relaxation technique in a dilution refrigerator. Special care was taken for the calibration of the RuO₂ thermometer attached to the sapphire disk serving as the sample platform in external magnetic fields. For this purpose, a calibrated temperature sensor was mounted inside a multilayered superconducting magnetic shield, which was located outside of the core of the magnet solenoid, but was thermally shortcut to the calorimeter. The specific heat of the sample platform alone has been measured in a separate experiment and was only a few ppm of the total measured specific heat at all temperatures and all fields. The absolute accuracy of the calorimeter is better than 3% at the lowest temperatures and further improves with increasing temperature.

This experimental setup allows for C_p -measurement scans either parallel to B in the T - B phase diagram by varying the temperature in a fixed magnetic field or vice versa, thus providing a good sensitivity to thermodynamic features in any direction of the phase diagram.

The sample has been cut from a piece of material used in a previous investigation of the specific heat.⁴ The specific heat in zero field and above 0.07 K is well described by $C_p = \gamma_0 T + \beta_{el} T^3$. Earlier measurements of the specific heat of UBe₁₃ had indicated that C_p is sample dependent such that the apparent linear term $\gamma_0 T$ arises from resonant scattering at impurities, imperfections, etc.^{6,17,18} The fit parameters γ_0 and β_{el} of the zero-field data presented here are consistent with those obtained in earlier measurements.⁶

In Fig. 1, we show the low-temperature specific heat as measured for $0.08 \leq T \leq 0.20$ K and $0 \leq B \leq 7$ T, as (a) a function of temperature at constant magnetic fields and (b) at constant temperatures vs field. The slight upturn at low T and high B is due to the nuclear Zeeman contribution of the Be atoms.

For field scans at constant T [Fig. 1(b)], $C_p(B)$ shows a broad shoulderlike feature centered around $B \approx 3$ T. In a recent study¹⁹ of the specific heat of UBe₁₃ in magnetic fields at somewhat higher temperatures, similar features of $C_p(T, B)$ at $B \approx 2$ T have been reported and were interpreted as an indication for the occurrence of a second phase in superconducting UBe₁₃. In Ref. 20, the results of thermal expansion and specific heat measurements have been combined to show the existence of an additional feature in the phase diagram of UBe₁₃. Below, we find further evidence for the existence of an additional feature in the phase diagram of UBe₁₃, which might be related to the shoulderlike feature, but which appears at slightly different B .

In this work, we are mainly interested in the magnetic-field induced electronic contribution to the specific heat, $C_H(T, B)$. The Be nuclei carry a nuclear spin, causing a magnetic field dependent and, especially at high fields and low temperatures, non-negligible contribution to the specific heat, $C_N(T, B)$, which is proportional to $B^2 T^{-2}$ and is discussed in great detail in Ref. 21. Aiming only at the magnetic-field induced electronic contribution, we consider

$$C_H(T, B) = C_p(T, B) - C_p(T, 0) - C_N(T, B), \quad (3)$$

FIG. 1. Representative data of the as-measured total specific heat of UBe₁₃ (a) vs T in constant magnetic fields and (b) vs magnetic field at constant temperatures.

where $C_p(T, B)$ is the measured specific heat, $C_N(T, B)$ the evaluated nuclear contribution and $C_p(T, 0)$ the measured specific heat in zero field. This procedure for obtaining the magnetic-field induced electronic contribution, $C_H(T, B)$, to be discussed below does not depend on any fit parameters or unknown background contributions and, therefore, leads to reliable results of $C_H(T, B)$.

According to Eq. (1), in the limit of $T \ll T_c$ and $B \ll B_{c2}$ the magnetic-field induced electronic specific heat should vary linearly with T . Thus, we have plotted $C_H(T, B)/T$ vs T measured at constant fields in Fig. 2. The discrepancy between the theoretical predictions and the experimental data is obvious. The model leading to Eq. (1) is expected to be valid only in the limit where $k_B T \ll \Delta E_D$, i.e., $x \sim T/T_c \sqrt{B_{c2}/B} \ll 1$.¹⁴ Setting the magnetic field to $B = B_{c2}/5$, which is already at the upper limit of the valid regime, the condition $x \leq \frac{1}{5}$ can only be fulfilled if $T/T_c \leq 0.09$. The critical temperature of the present material is $T_c = 0.91$ K. Thus, for the model to be applicable, the temperature has to be below 0.08 K, the lower limit of the temperature range covered in these experiments. This upper limit of the temperature decreases further with decreasing magnetic field and therefore, in this model's context and using these data no conclusions concerning the topology of possible gap nodes can be drawn.

FIG. 2. Magnetic field induced contribution to the specific heat C_H in constant magnetic fields divided by T vs temperature for various fields.

A more general approach to analyze the topology of possible gap nodes which is not only valid in the limit $x \ll 1$ but for all x , is provided by the universal scaling relation given in Eq. (2). According to Eq. (2), $C_H(T, B)/T^{2-D}B^{1/2}$ should be proportional to a universal function of the parameter $x \sim T/T_c \sqrt{(B_{c2}/B)}$. Although this scaling relation has theoretically only been demonstrated to be valid for $T \ll T_c$ and $B \ll B_{c2}$, we have plotted our entire $C_H(T, B)$ data set versus $y = T/\sqrt{B}$, setting $D=0$ and $D=1$, respectively. The result for $D=0$ is shown in Fig. 3. While the open symbols represent the magnetic field scans at constant T , the full symbols correspond to the temperature scans at constant B . We may separate the investigated field regime into a low-field part

FIG. 3. Scaling plot of the magnetic-field induced contribution to the specific heat for point nodes (see text). The open symbols represent measurements at constant temperatures ($T=0.107$, 0.147 , and 0.2 K from the left to the right) as a function of magnetic field and the full symbols are results obtained in constant magnetic fields as a function of temperature ($B=1.5$, 1.7 , 2 , 2.2 , 2.5 , 2.7 , 3 , 4 , 5 , 6 , and 7 T, from the bottom to the top). Inset: Similar scaling plot but for line nodes. The units on the y axes are $J \text{ mole}^{-1} \text{ K}^{-2} \text{ T}^{-1/2}$. The open and full symbols have the same meaning as in the main figure.

FIG. 4. Derivative of the magnetic-field induced specific heat C_H with respect to the temperature at $T=0.15$ K vs magnetic field. The solid line is a power law fit to the data below 2 T, revealing an exponent of $5/3$. A remarkable change may be seen at $B \approx 2$ T at which the change of behavior observed in the scaling plot (Fig. 3).

($B < B^* \approx 2$ T) and a high-field part. Inspecting Fig. 3 it turns out that all the data collapse onto a single common curve, except for those obtained at $B < B^*$, where the scaling behavior according to Eq. (2) is not obeyed at all. We note that in Fig. 3 also data for fields up to $B \approx B_{c2}/2$ are shown, but even for the highest fields applied here, the data reveal the scaling behavior. This scaling with respect to the scaling variable $T/\sqrt{B}$ is rather unique and implies the occurrence of nodes in the superconducting energy gap. Since this scaling is appropriate for $D=0$, we conclude that for $B > B^*$ the energy-gap function of superconducting UBe_{13} exhibits point nodes. Hence, we assume that the scaling prediction of Eq. (2) is more robust than previously expected and holds up to $B < B_{c2}/2$. In the region of the $B-T$ phase diagram of superconducting UBe_{13} where $B < B^*$ and at the lowest temperatures, we cannot make any claims about the topology of possible gap nodes. We note, however, that the broad shoulderlike feature reported in Fig. 1(b) is most probably related to this distinct change in the scaling behavior as may be seen in Fig. 3. In the investigated temperature range, some type of crossover from $B < B^*$ to $B > B^*$ at $B^* \approx 2$ T is also apparent, if we inspect the temperature derivative of $C_H(T, B)$ and display it in a plot of $\partial C_H/\partial T|_{T=\text{const}}$ vs B (Fig. 4). For $B < B^*$, the data are rather well described by a power law as indicated by the solid line in Fig. 4, whereas for $B > B^*$, the behavior is distinctly different. At present, the origin of this crossover at 2 T remains unclear.

As a test, the same procedure, but setting $D=1$, has been applied to both sets of data. No evidence for a scaling behavior in the whole investigated magnetic field and temperature range has been obtained, as may be seen in the inset of Fig. 3.

In the mixed state of a superconductor, a contribution to the specific heat might also arise from the low lying excitations localized near the core of the vortex. This problem has been discussed for s -wave superconductors by Caroli *et al.*²²

and by Bardeen *et al.*²³ According to that work, the lowest excitation level is expected at $E_0 \approx \Delta^2/E_F$, where Δ denotes the energy gap far away from the vortex. It is well established^{4,24} and has recently been confirmed²⁵ that UBe₁₃ is a strong coupling superconductor, which implies that the energy-gap amplitude is substantially larger than the BCS weak-coupling value of $\Delta \approx 1.76k_B T_c$. The Fermi-energy of UBe₁₃, given by E_F/k_B , is of the order of 10 K.⁴ Using these values and the predictions for *s*-wave superconductors, we find the lowest level of the low-energy excitations in the vortex core to be at significantly higher energies than the typical thermal energies $k_B T$ of this experiment. Furthermore, the observed scaling behavior with respect to $TB^{-1/2}$ is, as discussed above, rather unique, and cannot be associated with the mentioned vortex-core contribution.¹⁶

In conclusion we note, that for magnetic fields $B > B^* \approx 2$ T the magnetic-field induced contribution to the specific

heat exhibits a scaling behavior with respect to the scaling parameter $T/\sqrt{B}$ which, according to Eq. (2) for $D=0$, suggests the existence of pointlike nodes in the superconducting energy gap of UBe₁₃. No scaling could be established for the superconducting state of UBe₁₃ at low temperatures and $B < B^*$. A crossover behavior at $B = B^*$ is also observed in the $\partial C_H/\partial T$ vs B data. The same data set gives no similarly convincing evidence for the existence of nodes with $D > 0$, in any regime of the $B-T$ phase diagram.

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

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