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Journal
Journal of Physics Conference Series, 273(1)

ISSN
1742-6588

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Publication Date
2011

DOI
10.1088/1742-6596/273/1/012077

Low-temperature thermal conductivity of the noncentrosymmetric superconductor $LaRhSi_3$

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Abstract. We report on low-temperature thermal conductivity of the noncentrosymmetric superconductor $LaRhSi_3$ ($T_c = 2.3\,K$), which is a paramagnetic analog of the pressure-induced superconductor $CeRhSi_3$. In the normal state (either in zero field above T_c, or in magnetic field above H_{c2}), the thermal conductivity κ is mostly due to electrons, and shows a nearly T-linear dependence. In the superconducting state, κ decreases exponentially below T_c, and crosses over to $\kappa \propto T^2$ behavior at $T \ll T_c$. The temperature dependence of thermal conductivity of $LaRhSi_3$ is similar to that of a number of conventional s-wave superconductors. The field dependence of the residual linear term κ_0/T as a function of magnetic field suggests that $LaRhSi_3$ has no nodes in the superconducting gap.

1. Introduction

The discovery of the heavy fermion superconductor $CePt_3Si$ [1] has triggered intensive research efforts aimed to understand how the lack of crystal inversion symmetry affects the superconducting (SC) properties. The lack of an inversion center, a key symmetry for Cooper pairing, is mainly reflected in the electronic properties through the antisymmetric spin-orbit coupling (ASOC). This has an important influence on the electronic band structure therefore influencing both, the normal and the superconducting state. Several unusual properties appear in noncentrosymmetric superconductors (NCS) depending in particular on the specific form of the spin-orbit coupling as well as on the pairing symmetry. A Cooper pairing model with a two-component order parameter composed of spin-singlet and spin-triplet pairing components has been suggested [2, 3] in order to account for the unusual physical properties.

Interestingly, all of the NCS superconductors discovered so far among the f-electron systems, with the exception of $CePt_3Si$ [1], exhibit superconductivity only under applied pressure, p [4−8]. Among the remarkable characteristics of these compounds, probably associated with ASOC, are the large upper critical field H_{c2} exceeding the Pauli-Clogston paramagnetic limit, H_p and its anisotropy, as reported for $CeTSi_3$ ($T =$ Rh, Ir) [9, 10] and $CeTGe_3$ ($T =$ Co, Ir) [8, 11]. Therefore, paramagnetic depairing is not the main pair braking mechanism in these compounds as expected for a significant triplet component of the order parameter. In the presence of magnetic f-electrons, however, the SC paring mechanism could be coupled to a magnetic instability, which makes the role of crystal inversion symmetry unclear. However, noncentrosymmetric superconductivity extends also outside the heavy fermion class. Among the NCS transition-metal compounds, where electrons are not strongly correlated, Li_2Pt_3B was reported to be unconventional with line nodes and spin-triplet pairing [12, 13], whereas a number of others fall into the class of s-wave superconductors [14−16]. At present, there is no clear indication of whether the strong ASOC alone can result in unconventional superconductivity.

A NCS superconductor $LaRhSi_3$ ($T_c = 2.3$ K) without magnetic f-electron provides another opportunity to examine the effect of the violation of the inversion symmetry on the superconducting state, and to compare its behavior to that of the p-induced f-electron superconductor $CeRhSi_3$ [5, 9]. Here, we report on thermal conductivity measurements on a single crystalline $LaRhSi_3$. Thermal conductivity is a bulk probe of low energy delocalized excitations and a good tool to probe the SC gap symmetry.

2. Experimental details

Single crystals of $LaRhSi_3$ with tetragonal $BaNiSn_3$-type structure were grown by a Sn-flux method. Bulk superconductivity with $T_c = 2.3$ K was confirmed by a specific heat jump and a sharp resistance drop. No signature of Sn inclusions have been revealed by resistivity investigations. Thermal conductivity was measured down to 60 mK on a $1 \times 0.1 \times 0.1\,\mathrm{mm}^3$ parallelepiped crystal by a standard one-heater and two-thermometers technique. Heat current q was flowing in a direction parallel to [100]. Thermal links from the sample to the heater, thermometers, and the bath were provided by Pt wires spot-welded to the sample. Thermal isolation of the heater and RuO_2 thermometers from the support frame was achieved by using superconducting NbTi filaments. Electrical resistivity was measured with the electrical current $J \parallel [100]$, using the same crystal and as electrical contacts the same Pt wires used for the thermal conductivity measurement. Magnetic field $H \parallel [001]$ ensures that $H \perp q$.

3. Results and Discussion

Figure 1 shows the temperature dependence of thermal conductivity $\kappa(T)$ of $LaRhSi_3$ in zero field and in the normal state at $H = 40$ mT well above the upper critical field $H_{c2}(0) = 20$ mT. The heat current and the magnetic field were applied perpendicular to each other and in the directions $q \parallel [100]$ and $H \parallel [001]$. For the non-magnetic compound $LaRhSi_3$, we expect that the measured κ can be expressed as $\kappa = \kappa_e + \kappa_{ph}$, where κ_e and κ_{ph} are contributions from the delocalized thermal excitations of electrons and phonons, respectively. In zero field above T_c, $\kappa(T)$ shows close to T-linear behavior, which extends to the lowest temperature of our investigation when the superconductivity is suppressed at $H = 40$ mT. In the normal state, κ_e can be calculated via the Wiedemann-Franz (WF) law, which correlates thermal and charge conductivity in the normal state, as $\kappa_e = L_0T/\rho$, with $L_0 = 2.44 \times 10^{-8}\,\mathrm{W\Omega/K^2}$ the Lorenz number and ρ the measured resistivity. In $LaRhSi_3$, the estimated κ_e, indicated by open triangles, accounts almost completely for experimentally measured thermal conductivity in the normal state. Therefore, we can conclude that the normal state thermal conductivity κ_n is dominated by electrons ($\kappa_n \approx \kappa_e$). In the superconducting state, κ follows a BCS-like expression $\exp(-a\,T_c/T)$ with $a = 1.4$ (dotted curve) down to 0.7 K. Below 0.7 K ($T \ll T_c$), κ deviates from the exponential form, and exhibits phonon-like $\kappa \propto T^2$ behavior down to the lowest temperature. The overall temperature dependence of κ in $LaRhSi_3$ is qualitatively comparable to that of typical s-wave superconductors [17]. As an example, thermal conductivity of Aluminum ($T_c = 1.2$ K, $\kappa_n \approx \kappa_e \propto T^1$, $a = 1.5$, and $\kappa \propto T^{2.4}$ at $T \ll T_c$) [18] is shown in the inset of Fig. 1.

In conventional s-wave superconductors, $\kappa(T)$, dominated by electrons in the normal state, exponentially decreases upon opening the SC gap, and becomes negligible compared to the phonon contribution κ_{ph} at $T \ll T_c$. Here, we estimate the upper limit of κ_{ph} of $LaRhSi_3$ based on the scattering off the sample boundaries. Using the phonon specific heat

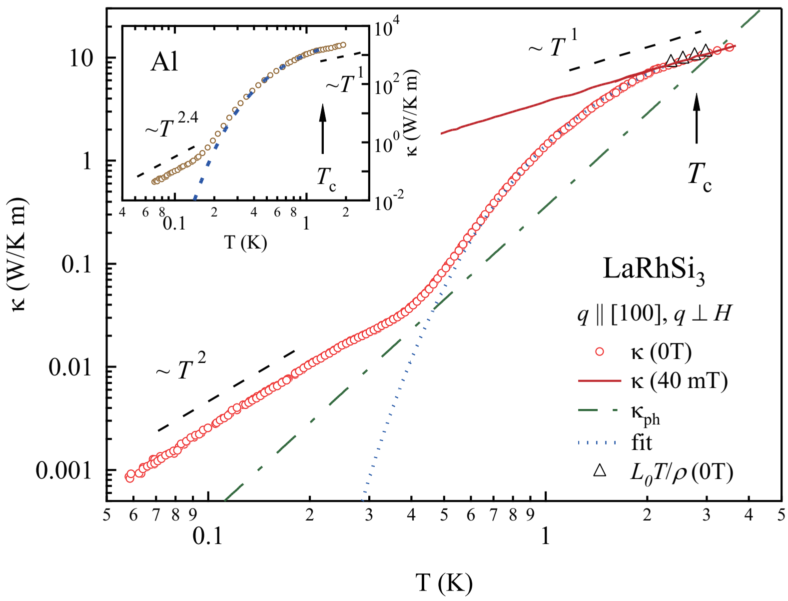

Figure 1. (Color online) Temperature dependence of the thermal conductivity $\kappa(T)$ of $LaRhSi_3$ for heat current $q \parallel [100]$ in zero field and at $40\,\mathrm{mT} \gg H_{c2}$ for $H \perp [100]$. The arrow indicates $T_c = 2.3\,\mathrm{K}$, determined from the specific heat and resistivity measurements. Open triangles represent the electronic conductivity in the normal state, obtained via the Wiedemann-Franz law from resistivity. A dotted line shows a fit to κ with $\kappa = C\exp(-a\,T_c/T)$ [17]. A dashed-dotted line corresponds to the phonon conductivity estimate for boundary scattering. Dashed lines are guides to eye, representing several $\propto T^n$ variations. The inset shows $\kappa(T)$ of Al ($T_c = 1.2\,\mathrm{K}$) [18].

coefficient $\beta = 2.68\,\mathrm{J/K^4\,m^3}$, mean phonon velocity $\langle v \rangle = 3570\,\mathrm{m/s}$ [19] and the phonon mean free path $l_{ph} = 1.13 \times 10^{-4}\,\mathrm{m}$, $\kappa_{ph} = \frac{1}{3}\beta T^3 \langle v \rangle\, l_{ph} = 0.36 \times 10^{-4} \times T^3\,\mathrm{W/K\,m}$ was obtained, and is indicated by a dashed-dotted line in Fig. 1. The estimated κ_{ph} is relatively close to the experimental κ at 0.4 K, although the experimental value ($n = 2$) is markedly different from theoretical one ($n = 3$). The reduction of the exponent value could be due to specular reflection of the phonon assuming that the faces of a crystal are smooth [20]. Another possibility is phonons scattering off either grain boundaries or electrons which are expected to give $n = 2$ [17], or combination of boundary scattering, phonon, and electron scattering. Further study should be performed to disentangle this issue.

Figure 2 displays the normalized residual linear term of thermal conductivity $(\kappa_0/T)/(\kappa_n/T)$ of $LaRhSi_3$ for $H \perp q$ as a function of the normalized field H/H_{c2}. κ_0/T was obtained by $T = 0$ extrapolation of the low-temperature κ/T data using an expression $\kappa/T = \kappa_0/T + bT^2$ at each field (not shown). κ_n/T is the normal state value estimated at $H_{c2} = 20\,\mathrm{mT}$. In s-wave superconductors, at low field above H_{c1}, quasiparticles are mostly localized around the vortex cores and cannot carry heat. When the applied field increases and the intervortex spacing is decreased, and quasiparticles begin to move between the vortices. This is the main reason why κ_0/T exhibits a sharp increase toward κ_n/T when field approaches H_{c2}, as can be seen for Nb data [21]. On the other hand, a remarkably rapid increase of κ_0/T at low field for nodal superconductor $Tl_2Ba_2CuO_{6+\delta}$ (Tl-2201) [22] comes from the excitation of nodal quasiparticles via Volovik effect [23]. A roughly field independent κ_0/T in $LaRhSi_3$ for fields below $\approx 0.65\,H_{c2}$ and a sharp rise above this field is most likely due to a weak Type II nature of superconductivity in this compound, with $H_{c1} \approx 0.65\,H_{c2}$. The overall field dependence of the residual linear term

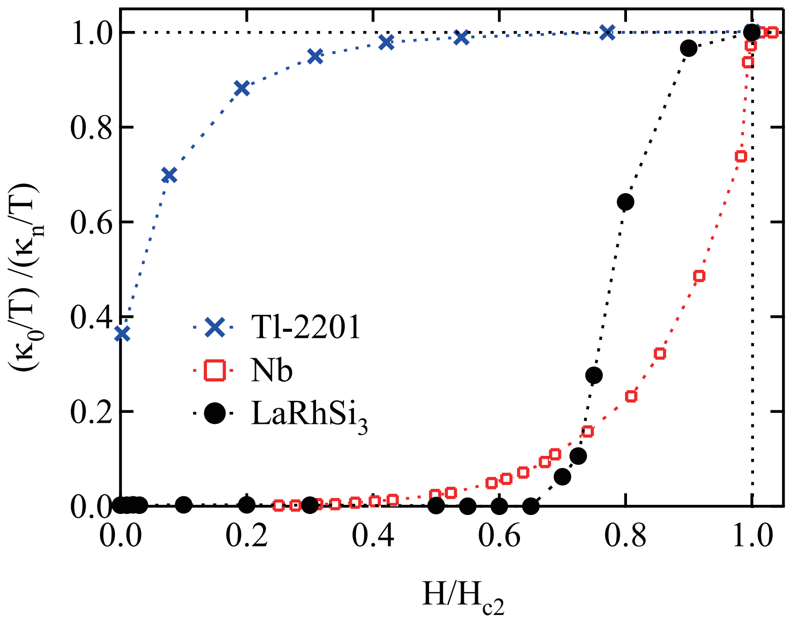

Figure 2. (Color online) Normalized residual linear term $(\kappa_0/T)/(\kappa_n/T)$ versus normalized field H/H_{c2} of $LaRhSi_3$ for $H \perp q$. κ_n/T is the normal state value extrapolated to $T \to 0$ at $H_{c2} = 20\,mT$. For comparison, data for several superconductors with different gap structures are also displayed: Nb (clean, fully gapped *s*-wave) [21], Tl-2201 (*d*-wave with line nodes) [22].

suggests that the superconducting gap in full open in $LaRh_3Si$

A similar approach of comparing the SC gap structures in isostructural compounds without and with *f*-electrons, was taken via penetration depth measurements on $LaPt_3Si$ and $CePt_3Si$ [24], respectively. The results indicated that $LaPt_3Si$ is a conventional *s*-wave superconductor, in contrast to the unconventional superconductivity with line nodes found in $CePt_3Si$ [24–26].

4. Conclusion

To conclude, we have performed a low-temperature magneto-thermal conductivity measurement of a noncentrosymmetric superconductor $LaRhSi_3$. A roughly field-independent residual thermal conductivity at $H < 0.65\,H_{c2}$ is consistent with $LaRhSi_3$ being a weakly Type II superconductor with $H_{c1} \approx 0.65\,H_{c2}$ at $T = 0$. The field evolution of the residual T-linear term suggests that no nodes are present in the superconducting gap. The temperature dependence of thermal conductivity in $LaRhSi_3$ at zero field is similar in many aspects to that of conventional *s*-wave superconductors. Further studies are required to ascertain whether superconductivity in $LaRhSi_3$ is unconventional.

References

[1] Bauer E, Hilscher G, Michor H, Paul Ch, Scheidt E W, Gribanov A, Seropegin Yu, Noël H, Sigrist M and Rogl P 2004 *Phys. Rev. Lett.* **92** 027003
[2] Frigeri P A, Agterberg D F, Koga A and Sigrist M 2004 *Phys. Rev. Lett.* **92** 097001
[3] Hayashi N, Wakabayashi K, Frigeri P A and Sigrist M 2006 *Phys. Rev. B* **73** 024504
[4] Akazawa T, Hidaka H, Fujiwara T, Kobayashi T C, Yamamoto E, Haga Y, Settai R and Ōnuki Y 2004 *J. Phys.: Condens. Matter* **16** L29.
[5] Kimura N, Ito K, Saitoh K, Umeda Y and Aoki H 2005 *Phys. Rev. Lett.* **95** 247004

[6] Sugitani I, Okuda Y, Shishido H, Yamada T, Thamizhavel A, Yamamoto E, Matsuda T D, Haga Y, Takeuchi T, Settai R and Ōnuki Y 2006 *J. Phys. Soc. Jpn.* **75** 043703
[7] Settai R, Okuda Y, Sugitani I, Ōnuki Yi, Matsuda T D, Haga Y and Harima H 2007 *Int. J. Mod. Phys. B* **21** 3238
[8] Honda F, Bonalde I, Yoshiuchi S, Hirose Y, Nakamura T, Shimizu K, Settai R and Ōnuki Y 2009 *Physica C* to be published
[9] Kimura N, Ito K, Aoki H, Uji S and Terashima T 2007 *Phys. Rev. Lett.* **98** 197001
[10] Settai R, Miyauchi Y, Takeuchi T, Levy F, Sheikin I and Ōnuki Y 2008 *J. Phys. Soc. Jpn.* **77** 073705
[11] Méasson M -A, Muranaka H, Kawai T, Ota Y, Sugiyama K, Hagiwara M, Kindo K, Takeuchi T, Shimizu K, Honda F, Settai R and Ōnuki Y 2008 *J. Phys. Soc. Jpn.* **78** 124713
[12] Yuan H Q, Agterberg D F, Hayashi N, Badica P, Vandervelde D, Togano K, Sigrist M and Salamon M B 2006 *Phys. Rev. Lett.* **97** 017006
[13] Nishiyama M, Inada Y and Zheng G -q 2007 *Phys. Rev. Lett.* **98** 047002
[14] Klimczuk T, Ronning F, Sidorov V, Cava R J and Thompson J D 2007 *Phys. Rev. Lett.* **99** 257004
[15] Harada A, Tamura N, Mukuda H, Kitaoka Y, Wakui K, Akutagawa S and Akimitsu J 2009 *J. Phys. Soc. Jpn.* **78** 025003
[16] Bauer E, Khan R T, Michor H and Royanian E 2009 *Phys. Rev. B* **80** 064504
[17] See, for example, Berman R 1976 *Thermal conduction in Solids (Oxford Univ. Press, Oxford)*
[18] Movshovich R, Hubbard M A, Salamon M B, Balatsky A V, Yoshizaki R, Sarrao J L and Jaime M 1998 *Phys. Rev. Lett.* **80** 1968.
[19] Miclea C F *et. al.* unpublished
[20] Pohl R O and Stritzker B 1982 *Phys. Rev. B* **25** 3608
[21] Lowell J and Sousa J B 1970 *J. Low. Temp. Phys.* **3** 65
[22] Proust C, Boaknin E, Hill P W, Taillefer L and Mackenzie A P 2002 *Phys. Rev. Lett.* **89** 147003
[23] Volovik G E 1995 *JETP Lett.* **58** 469
[24] Ribeiro R L, Bonalde I, Haga Y, Settai R and Ōnuki Y 2009 *J. Phys. Soc. Jpn.* **78** 115002
[25] Bonalde I, Brämer-Escamilla W and Bauer E 2005 *Phys. Rev. Lett.* **94** 207002
[26] Izawa K, Kasahara Y, Matsuda Y, Behnia K, Yasuda T, Settai R and Ōnuki Y 2005 *Phys. Rev. Lett.* **94** 197002