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Line Nodes in the Superconducting Gap Function of Noncentrosymmetric CePt$_3$Si

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The superconducting gap structure of recently discovered heavy fermion CePt$_3$Si without spatial inversion symmetry was investigated by thermal transport measurements down to 40 mK. In zero field a residual T-linear term was clearly resolved as $T \to 0$, with a magnitude in good agreement with the value expected for a residual normal fluid with a nodal gap structure, together with a T^2 dependence at high temperatures. With an applied magnetic field, the thermal conductivity grows rapidly, in dramatic contrast to fully gapped superconductors, and exhibits one-parameter scaling with $T/\sqrt{H}$. These results place an important constraint on the order parameter symmetry; that is, CePt$_3$Si is most likely to have line nodes.

The superconducting gap structure of heavy fermion (HF) superconductors is very important in understanding the physics of unconventional superconductivity in strongly correlated systems [1,2]. Very recently a new HF superconductor CePt$_3$Si with $T_c = 0.75$ K has been discovered [3]. CePt$_3$Si has aroused great interest because it possesses quite unique properties. The most noticeable feature is the absence of spatial inversion symmetry, in contrast to most unconventional superconductors. It is well known that in the presence of strong spin-orbit interaction, the absence of inversion symmetry gives rise to a splitting of the two spin degenerate bands. It has been shown that the lifted spin degeneracy strongly influences the pairing symmetry of Cooper pairs [3–12]. For example, Rashba-type spin-orbit interaction dramatically changes the paramagnetic effect, which breaks up Cooper pairs [5–9]. A subsequent band structure calculation for CePt$_3$Si indicates a very strong spin-orbit coupling [10]. The special interest in the symmetry of CePt$_3$Si has arisen with the observation that the upper critical field $H_{c2} \sim 4$ T drastically exceeds the Pauli paramagnetic limit $H_P \sim 1.3 k_B T_c/\mu_B \sim 1$ T [3]. Moreover, recent NMR measurements have reported no change of the Knight shift below T_c for $H \parallel c$ [13]. These results indicate that the paramagnetic effect on Cooper pairs is absent or is strongly reduced in CePt$_3$Si. Generally, in the system without inversion symmetry the gap function is a mixture of spin-singlet and spin-triplet channels in the presence of a finite spin-orbit coupling strength. The main channel of the gap function of CePt$_3$Si has been analyzed in the light of either spin-triplet or spin-singlet pairing [3,7–10,12]. Moreover, peculiar properties, including nonuniform helical superconducting phases and the Zeeman-field-induced supercurrent [14], have been proposed in association with the lack of inversion symmetry [15].

Apart from exhibiting noncentrosymmetric superconductivity, CePt$_3$Si undergoes a superconducting transition after antiferromagnetic ordering with local moments,

$\sim 0.2\mu_B$–$0.3\mu_B$/Ce, occurs at $T_N = 2.2$ K [3]. The ordered moments are coupled ferromagnetically in the tetragonal ab plane and are stacked antiferromagnetically along the c axis [16]. In UPd$_2$Al$_3$ with a similar coexistence, strong coupling between superconductivity and spin wave excitation has been reported, and the gap function $\Delta \propto \cos k_z c$ indicates pairing between adjacent layers [2,17]. Therefore, the relation between the superconductivity and the local moment in CePt$_3$Si is an intriguing issue.

A major outstanding question about CePt$_3$Si is the nature of the superconducting gap structure, which is of primary importance for understanding the peculiar superconducting state associated with broken inversion symmetry. The spin-triplet pairing state with point nodes, $\boldsymbol{d(k)} = \hat{\boldsymbol{x}}k_y - \hat{\boldsymbol{y}}k_x$, has been proposed as a candidate for the gap function [3,7]. Recent experiments of NMR relaxation rate $1/T_1$ in CePt$_3$Si suggest a new class of superconducting state with a point-node gap function [16]. In this Letter, we report on thermal transport measurements down to 40 mK in order to clarify the gap structure of CePt$_3$Si. We provide a strong indication of line nodes in CePt$_3$Si, in contrast to the previous studies.

Single crystals of CePt$_3$Si were grown by the Bridgeman method. Clear de Haas–van Alphen oscillation was observed at low temperatures in a sample from the same batch, confirming the high quality of the sample. The thermal conductivity κ was measured between 40 mK and 3 K for a heat current $\boldsymbol{q} \parallel a$ axis of the tetragonal structure in the $H \parallel b$ axis.

The insets of Figs. 1(a) and 1(b) show the a axis resistivity ρ and κ. Below T_N, ρ exhibits Fermi liquid behavior, $\rho \propto T^2$. At 50 mK, H_{c2} determined by ρ is slightly below 4 T. Figure 1 and the inset of Fig. 2(b) depict the T dependence of κ/T. In zero field, κ/T exhibits a broad minimum at T_N, shows no significant change at T_c, and decreases rapidly with decreasing T after exhibiting a maximum just below T_c. In order to use κ as a probe of
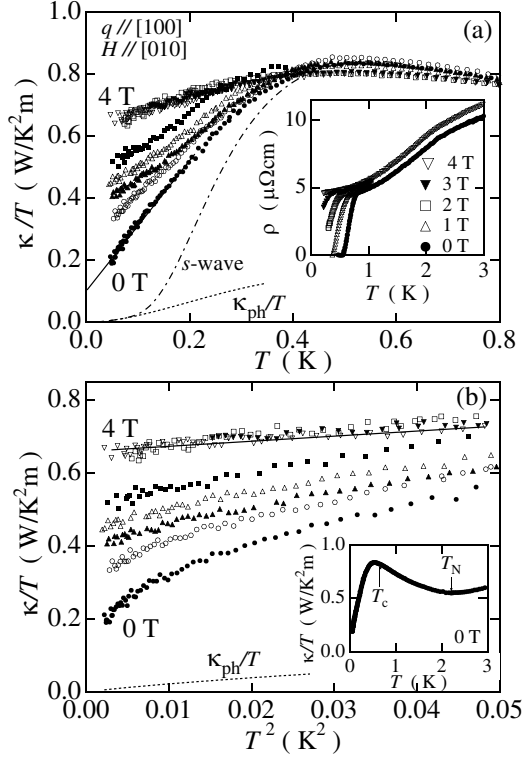
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FIG. 1. (a) Main panel: *a*-axis thermal conductivity of CePt$_3$Si for the $H \parallel b$ axis, plotted as κ/T vs T (●, 0 T; ○, 0.2 T; ▲, 0.5 T; △, 1 T; ■, 1.5 T; □, 2 T; ▼, 3 T; ▽, 4 T). The solid line is a linear fit in zero field: $\kappa/T = A + BT$. The dashed line is the contribution of phonons κ_{ph}. The dash-dotted line is the thermal conductivity in *s*-wave superconductors. Inset: T dependence of *a*-axis resistivity for the $H \parallel b$ axis. (b) The same data at low temperatures plotted as κ/T vs T^2. The solid line is a linear fit in the normal state: $\kappa/T = a + bT^2$. The dashed line represents κ_{ph}. Inset: T dependence of κ/T in zero field.

quasiparticle behavior, the phonon and antiferromagnetic magnon contributions must be extracted reliably. The magnon contribution is negligibly small at $T < 1$ K, since the spin wave gap in CePt$_3$Si is reported to be larger than 15 K [16]. The simplest way to estimate the phonon conductivity is to separate the phonon κ_{ph} and electron κ_e contributions in the normal state at a temperature sufficiently low that κ_{ph} has reached its well defined asymptotic T^3-dependent value given by $\kappa_{ph} = \frac{1}{3}\beta\langle v_s\rangle T^3 \ell_{ph}$, where β is the phonon specific heat coefficient, $\langle v_s \rangle$ is the mean acoustic phonon velocity, and ℓ_{ph} is the phonon mean free path. In Fig. 1(b), κ/T is plotted as a function of T^2. The solid line is a linear fit in the normal state, $\kappa/T = a + bT^2$ with $a = 0.65$ W/K^{2}m and $b = 1.4$ W/K^{4}m. Using $\langle v_s\rangle \sim 3000$ m/s and $\beta \simeq 10.8$ J/K^{4}m^3 yields $\ell_{ph} \sim 200$ μm, which is comparable to the sample size. Therefore the T^3 term in κ mainly originates from phonons. Note that the Lorentz number $L = \kappa\rho/T \simeq 1.02L_0$ at $T \to 0$ in the normal state is very close to the Sommerfeld value $L_0 = 2.44 \times 10^{-8}$ Ω W/K. The dashed lines in Figs. 1 and 2 show κ_{ph}. Based on these estimations, we can conclude
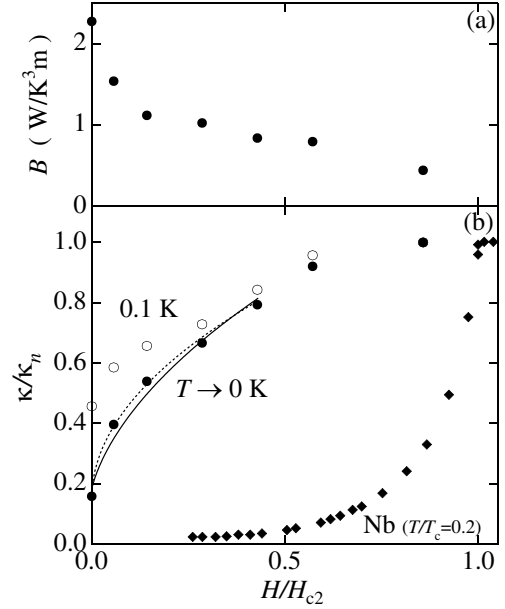

FIG. 2. (a) H dependence of the T-linear coefficient of $\kappa/T = A + BT$. (b) H dependence of κ, normalized by the normal state value κ_n, as a function of H/H_{c2} at $T = 100$ mK and at $T \to 0$. We used $H_{c2} = 3.6$ T. The dashed line represents $\kappa/\kappa_n = 0.15 + 0.54H^{0.49}$. The solid line is the result of fitting obtained by using Eq. (3). For comparison, data for the typical *s*-wave superconductor Nb at 2 K is shown (◆). For details, see the text.

that heat transport well below T_c is dominated by the electronic contribution: $\kappa \cong \kappa_e$.

We first discuss the thermal transport in zero field. As shown in Fig. 1(a), the T dependence of κ/T in CePt$_3$Si is markedly different from that in a fully gapped *s*-wave superconductor, in which κ/T exhibits exponential behavior [18]. As shown by the straight line in Fig. 1(a), κ/T is well fitted to the data by $\kappa/T = A + BT$ in a wide T range above 40 mK.

The presence of a residual term at $T \to 0$ in κ/T is clearly resolved. The residual term indicates the existence of a residual normal fluid, which is expected for an unconventional superconductor with nodes in the energy gap. This residual normal fluid is a consequence of impurity scattering, even for low concentrations of nonmagnetic impurities [19,20]. It has been shown that, for an order parameter with line nodes, the quasiparticle thermal conductivity has components that are universal in the limit $T \to 0$ and of the form

$$\frac{\kappa_e}{T} = \frac{\kappa_{00}}{T}\left(1 + O\left[\frac{T^2}{\gamma_0^2}\right]\right) \quad (1)$$

in the range $k_B T < \gamma_0$, where γ_0 is the impurity bandwidth [19–21]. κ_{00}/T is the residual term and the second T^2 term is a finite T correction, which strongly depends on the impurity scattering phase shift. We did not observe the T^2 term in κ/T in our T range. This may be due to the fact that γ_0 is comparable to or less than our lowest

temperature. In this case, the residual term extrapolated from the high temperature regime, assuming $\kappa/T = A + BT$, gives a lower limit of κ_{00}/T, while the value at κ/T at 40 mK gives the higher limit: $0.1 < \kappa_{00}/T < 0.2$ W/K^2 m. The magnitude of the residual term κ_{00}/T for unitary scattering with small γ_0 is given by

$$\frac{\kappa_{00}}{T} = \left(\frac{4}{\pi}\frac{\hbar\Gamma}{\Delta_0}\frac{1}{\mu}\right)\frac{\kappa_n}{T}. \tag{2}$$

Here κ_n is the normal state thermal conductivity, Δ_0 is the maximum of the energy gap, Γ ($\gamma_0 \simeq 0.61\sqrt{\hbar\Gamma\Delta_0}$) is the impurity scattering rate, and $\mu = 1/\Delta_0|d\Delta(\phi)/d\phi|_{\text{nodes}}$ is the slope parameter of the gap function at the node. This universal limit is the result of a compensation between the growth in the normal fluid density with increasing impurity concentration and the concomitant reduction in the mean free path of the quasiparticles [19–21]. The universal thermal conductivity has been reported for high-T_c cuprates [22] and Sr$_2$RuO$_4$ [23]. Using $\hbar\Gamma/\Delta_0 \simeq \pi\xi/2\ell_e \sim 0.16$ from de Haas–van Alphen [24] and H_{c2} measurements, κ_{00}/T is estimated to be ~ 0.09 W/K^2 m, where ξ is the coherence length and ℓ_e is the mean free path. This value is close to the observed $\kappa_{00}/T \sim 0.1$ W/K^2 m. Thus the residual conductivity is quantitatively consistent with a gap function with line nodes.

The T dependence of κ/T is intriguing. Instead of being T^2 (as predicted by theory), it is T linear. Long ago, it was argued that, in the presence of line nodes in the gap function, the linear energy dependence of the density of states (DOS) leads to a T-linear κ/T [25]. Experimentally, in several superconductors believed to host line nodes, such as CeCoIn$_5$ [26], CeIrIn$_5$ [27], and Sr$_2$RuO$_4$ [23,28], κ/T is Tlinear in a wide T range below T_c.

Strong indication for the presence of line nodes is provided by the H dependence of κ. Figure 2(b) depicts the H dependence of κ normalized by the normal state value κ_n at 100 mK and at $T = 0$ ($\kappa = \kappa_e$) obtained by the simple extrapolation to $T \to 0$. For comparison, we show in Fig. 2(b) the thermal conductivity of the typical s-wave superconductor Nb at 2 K [29]. The H dependence of κ/T in CePt$_3$Si is in dramatic contrast to that in Nb. In an s-wave superconductor, the only quasiparticle states present at $T \ll T_c$ are those associated with vortices. When vortices are far apart (H at $H \ll H_{c2}$), these states are bound to the vortex core and are therefore localized and unable to transport heat. Therefore the large amount of delocalized quasiparticles throughout the vortex state of CePt$_3$Si is immediately apparent. The H dependence of κ/κ_n at $T \to 0$ is well fitted by $\kappa/\kappa_n = 0.15 + 0.54H^{0.49}$ as shown by the dotted line in Fig. 2(b), indicating that the power law on H is very close to $1/2$. In Fig. 2(a), the H dependence of the T-linear coefficient of $\kappa/T(= A + BT)$ is shown. B decreases faster than $\sqrt{H}$. This may be important for understanding the origin of T-linear dependence of κ/T.

The understanding of the heat transport of superconductors with nodes has progressed considerably during the past few years [30–32]. In contrast to classical superconductors, the heat transport in nodal superconductors is dominated by contributions from delocalized quasiparticle states outside vortex cores. The most remarkable effect on the thermal transport is the Doppler shift of the energy of quasiparticles with momentum $\boldsymbol{p}$ in a circulating supercurrent flow $\boldsymbol{v}_s$ $[E(\boldsymbol{p}) \to E(\boldsymbol{p}) - \boldsymbol{v}_s \cdot \boldsymbol{p}]$ [33]. This effect (Volovik effect) becomes significant at positions where the local energy gap becomes smaller than the Doppler shift term ($\Delta < \boldsymbol{v}_s \cdot \boldsymbol{p}$), which can occur in superconductors with nodes. In the presence of line nodes, where the DOS of electrons $N(E)$ has a linear energy dependence [$N(E) \propto E$], $N(H)$ increases in proportion to $\sqrt{H}$. According to Kübert and Hirschfeld [31], the thermal conductivity at $T = 0$ in superconductors with line nodes increases as

$$\kappa(0, H) = \kappa_{00}\frac{p}{p\sqrt{1 + p^2} - \sinh^{-1}p} \tag{3}$$

with $p \equiv \sqrt{8\hbar\Gamma H_{c2}/\pi^2\Delta_0 H}$ for unitary limit scattering. The solid line in Fig. 2 indicates the field dependence of κ/T calculated from Eq. (3) using $\hbar\Gamma/\Delta_0 = 0.10$. The H dependence is quite well reproduced. We stress here that this $\hbar\Gamma/\Delta_0$ value is close to that used for estimating the universal thermal conductivity, indicating the consistency between the two different experiments.

To obtain further insight into the thermal conductivity in a magnetic field, we examined the scaling relation of the quasiparticle thermal conductivity with respect to T and H in accordance with Ref. [31]. At finite temperatures, the number of thermally excited quasiparticles exceeds that of Doppler shifted quasiparticles. This crossover field is roughly estimated by $\sqrt{H/H_{c2}} \sim k_B T/\Delta_0$. A scaling relation of the single variable $x = t/\sqrt{h}$ with $t = T/T_c$ and $h = H/H_{c2}$ is derived as

$$\kappa_e(T, H)/\kappa_e(T, 0) = F(x), \tag{4}$$

where $F(x)$ is a scaling function. Theoretically, Eqs. (3) and (4) are expected to be valid only in the $H \ll H_{c2}$ regime. As seen in Fig. 3, the experimental data give a satisfactory collapse for fields up to 1 T [$0.3H_{c2}(0)$] and for the $H = 1.5$ T data a deviation from this collapse appears [34]. We here obtained κ_e by subtracting κ_{ph} from κ at finite temperatures. Since no scaling is expected for a point node, the present $T/\sqrt{H}$ scaling again strongly indicates the presence of line nodes. We also note that the scaling behavior implies that scattering in CePt$_3$Si is in the unitary limit.

To summarize the salient features of the superconductivity of CePt$_3$Si: (1) a residual term in $\kappa(T, 0)/T$ as $T \to 0$ whose magnitude is in good agreement with the universal conductivity, (2) T-linear dependence of $\kappa(T, 0)/T$ at high temperatures, (3) H dependence well fitted by the theory of Doppler shifted quasiparticles, and (4) scaling relations in
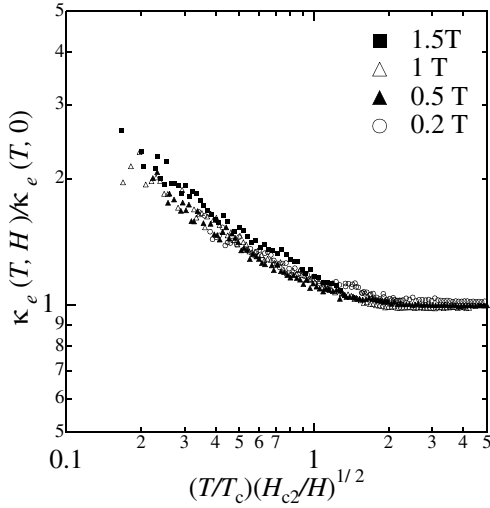
FIG. 3.   Scaling plot $F \equiv \kappa_e(T,H)/\kappa_e(T,0)$ vs $x = (T/T_c)/\sqrt{H/H_{c2}}$. Note that the data collapse into the same curve.

the variable $T/\sqrt{H}$. The combination of all these results lead us to conclude that the gap function of CePt$_3$Si has line nodes. Recently it has been reported that the T and H dependencies of the thermal conductivity in s-wave superconductors with multigaps, such as MgB$_2$ and NbSe$_2$, exhibit a strong deviation from those in s-wave superconductors with a single gap [36]. However, it is very unlikely that such a multigap scenario provides an explanation for the thermal conductivity in CePt$_3$Si. Indeed, the presence of a finite residual term in the zero-field temperature dependence of κ/T in temperatures as low as 40 mK puts an upper limit on the magnitude of any hypothetical second gap. Moreover, the scaling observed here is not expected in the multigap scenario. At this stage, it is safe to conclude that we are in the presence of a gap function with line nodes.

The possibility of the line node in CePt$_3$Si was first discussed in Ref. [10]. Recently it has been shown that the gap function in superconductors with lifted spin degeneracy can be expressed as $\Delta(\bm{k}) = \chi(\bm{k})t(\bm{k})$, where $\chi(\bm{k})$ is an even auxiliary function that transforms according to the irreducible representation and $t(\bm{k})$ is a model dependent phase factor [12]. The thermodynamic properties are determined by the orbital part of $\chi(\bm{k})$. The presence of line nodes is incompatible with the recent theoretical consideration of the spin-triplet gap function with $\bm{d}(\bm{k}) = \hat{\bm{x}}k_y - \hat{\bm{y}}k_x$ [which corresponds to $\chi(\bm{k}) = k_x^2 + k_y^2$] and NMR measurements, both of which suggest a point-node gap function.

In conclusion, we have investigated low energy quasiparticle excitation in CePt$_3$Si by thermal conductivity measurements. All the results provide a strong indication of line nodes in the gap function. Our results place strong constraints on models that attempt to explain the uncommon superconductivity without space inversion symmetry.

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