Chiral d-wave superconductivity in the heavy-fermion compound CeIrIn$_5$

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Abstract. - Recent thermal conductivity measurements in the heavy-fermion compound CeIrIn$_5$ indicate that its superconducting order parameter is very different from CeCoIn$_5$. Here we show that these experiments are consistent with chiral d-wave symmetry, i.e. $\Delta(\vec{k}) \sim e^{\pm i\phi}\cos(c k_z)$.

The discovery of antiparamagnon mediated superconductivity in the 115 heavy-fermion compounds CeTIn$_5$, where T represents Co, Ir, Rh, or a mixture of these, has recently opened up a new avenue to unconventional nodal superconductivity [1]. These strongly interacting materials are characterized by a plethora of competing ground states in addition to superconductivity, including conventional and unconventional spin density wave (SDW) phases [2]. Among the 115 compounds, the currently most well studied is CeCoIn$_5$ for which a d-wave superconducting order parameter $\Delta(\vec{k}) \sim \cos(2\phi) = \hat{k}_x^2 - \hat{k}_y^2$ has been identified [3–6]. Indeed, there are many parallels between CeCoIn$_5$ and the high-$T_c$ cuprates, including (a) a layered quasi-two-dimensional Fermi surfaces [7], (b) d-wave superconductivity, and (c) d-wave spin density wave order in the pseudogap phase [8–10].

Recent thermal conductivity measurements [11, 12] indicating an order parameter symmetry in CeIrIn$_5$ very different from the one in CeCoIn$_5$ came as a big surprise. An initial analysis of this data suggested a hybrid $E_g$ gap, $\Delta(\vec{k}) \sim Y_{2,\pm 1}(\theta, \phi)$, based on the assumption that the Fermi surface is three-dimensional. However, the Fermi surface of CeIrIn$_5$ is in fact quasi-two-dimensional, as known from band structure analysis [7,12]. Therefore, one needs to consider instead superconductivity in layered structures, similar as discussed in Refs. [13, 14]. In this case, only $f = e^{\pm i\phi}\sin(\chi)$ (chiral d-wave) with $\chi = c k_z$ or $f \sim \sin(\chi)$ (non-chiral p-wave) are consistent with the observed thermal conductivity data [11]. The magnitudes of the d-wave and chiral d-wave/non-chiral p-wave order parameters $|\Delta(\vec{k})|$ are shown in Fig. 1.

In the following, we present a theoretical analysis based on a generalized BCS model that properly accounts for a quasi-two-dimensional Fermi surface and a chiral d-wave superconducting order parameter. The thermal conductivity is computed following the receipt given in Refs. [14, 15]. Here, we assume for simplicity that the quasiparticle scattering is due to impurities. Furthermore, we consider the physically relevant limit $\Gamma/\Delta \ll 1$, where $\Gamma$ is the quasiparticle scattering rate in the normal state and $\Delta(= 0.856 K)$ is the maximum value of the energy gap at $T = 0 K$. This $\Delta$ is the weak-coupling value for nodal
superconductors \cite{13,16}.

Let us begin by considering the zero-temperature limit. For quasi-two-dimensional structures, the thermal conductivity strongly depends on the direction within the material. Therefore we will discuss the cases $\vec{q}\parallel\vec{a}$ (in-plane) and $\vec{q}\parallel\vec{c}$ (out-of-plane) separately. Here $\vec{q}$ denotes the heat current. For $\vec{q}\parallel\vec{a}$, one obtains

$$\frac{\kappa_a}{\kappa_a} = \frac{2\Gamma_a}{\pi\Delta},$$

(1)

and similarly for $\vec{q}\parallel\vec{c}$

$$\frac{\kappa_c}{\kappa_c} = 2\left(\frac{\Gamma_c}{\Delta}\right)^2,$$

(2)

where $\Gamma_a$ and $\Gamma_c$ denote the in-plane and out-of-plane scattering rates respectively. Eq.1 describes the universal heat conduction as discovered by P. Lee \cite{17,18}, whereas Eq.2 is very different. The strength of the impurity scattering can be extracted directly from the experimental data show in Fig. 2 of Ref. \cite{11}, from which we can deduce that $\frac{\Gamma_c}{\Delta} = 0.19635$.

Furthermore, from the observed anisotropy of the thermal conductivity, we can infer the ratio of the Fermi velocities along the c-axis and the a-b plane, i.e. $\frac{v_c}{v_a} = 0.66$, which is very similar to $\frac{v_c}{v_a} = 0.5$ extracted for CeCoIn$_5$ \cite{8}. Then, for $T \neq 0 K$ but $\frac{T}{\Delta} \ll 1$, we obtain in the regime $T \gg \Gamma$,

$$\frac{\kappa_a(T)}{\kappa_a(T)} = \frac{27}{2\pi^2}\zeta(3)\left(\frac{T}{\Delta}\right) + O\left(\frac{T}{\Delta}\right)^3,$$

(3)

and

$$\frac{\kappa_c(T)}{\kappa_c(T)} = \frac{45^2}{4\pi^2}\zeta(5)\left(\frac{T}{\Delta}\right)^5 + O\left(\frac{T}{\Delta}\right)^5.$$

(4)

This is consistent with the experimental observation of a dominant in-plane heat conductivity proportional to the temperature, and a subdominant out-of-plane conductivity.

In order to connect these finite-temperature results with the above equations for $T = 0$, we use an interpolation formula which applies in the regime for $T/\Delta(T) \ll 1$. The resulting low-temperature thermal conductivities are then given by

$$\frac{\kappa_a(T)}{\kappa_a(T)} = \frac{2\Gamma_a}{\pi\Delta}\left(1 + \left(\frac{27}{4\pi}\zeta(3)\frac{T}{\Gamma_a}\right)^2\right)^{1/2},$$

(5)
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Fig. 2: Thermal conductivity in the $\vec{q}||\vec{a}$ (in-plane) and $\vec{q}||\vec{c}$ (out-of-plane) directions. $T_c = 0.4K$. The symbols represent experimental data from [11], and the solid lines are low-temperature fits using Eqs. 5 and 6.

and

$$\frac{\kappa^c(T)}{\kappa^a_0(T)} = 2 \left( \frac{\Gamma_c}{\Delta} \right)^2 \left[ 1 + \left( \frac{45^2}{8\pi^2} \zeta(5) \frac{T}{\Gamma_c} \right)^2 \left( \frac{T}{\Delta} \right)^2 \right]^{1/2}$$

respectively.

In Fig. 2, we compare these dependencies with the experimental data reported in Ref. [11]. A fit of the low-temperature regimes yields good agreement with $\frac{\Gamma_c}{\Gamma_a} = 0.5592$. Evidently, the quasi-particle scattering rate is somewhat anisotropic in the present system. Here, the temperature dependence of the gap function $\Delta(T)$, is approximated by

$$\Delta(T) = 2.14T_c \left[ 1 - \left( \frac{T}{T_c} \right)^3 \right]^{1/2}$$

with $T_c = 0.4K$, which is known to be a very good approximation for d-wave superconductors [19].

Similarly, the ratio $\kappa^c(T)/\kappa^a(T)$ can be computed and compared to the experiments. Within our model, it is given by

$$\kappa^c(T)/\kappa^a(T) = 0.2703 \left[ 1 + \frac{45^2}{8\pi^2} \zeta(5) \right]^2 \left( \frac{T}{\Gamma_c} \right)^2 \left( \frac{T}{\Gamma_a} \right)^2 \left[ 1 + \frac{27}{4\pi} \zeta(3) \right]^2 \left( \frac{T}{\Delta} \right)^2 \right]^{1/2}$$

which is shown in Fig. 3 along with the thermal conductivity measurements of Ref. [11].

These expressions give a very reasonable description of the thermal conductivity for $T/T_c \leq 0.3$. We note that a similarly good description of the thermal conductivity is given by the hybrid gap proposed in Ref. [11]. At higher temperatures, $T/T_c \geq 0.3$, our simple model fails to describe the measured thermal conductivity, possibly due to the fact that phonons begin to play an important role as we approach $T \to T_c$. Nevertheless, we can conclude that chiral d-wave SC is consistent with the experimental data of Refs. [11, 12] in the relevant low-temperature regime. Note also, that our calculations predict an interesting upturn in the ratio $\kappa^c(T)/\kappa^a(T)$ as the temperature is further lowered. This prediction can
be scrutinized experimentally, and may serve as a means to distinguish the present theory from the hybrid gap model that was proposed earlier.

In the present context, the unconventional superconducting order in CeRhIn$_5$ is of great interest. Let us briefly contemplate on the doped case. Inspecting Fig. 3 of Ohira-Kawamura et al [12] we may conclude that the order parameter in CeRh$_{1-x}$Co$_x$In$_5$ should be d-wave SC with an angular dependence $f = \cos(2\phi)$, whereas the order parameter in CeRh$_{1-x}$Ir$_x$In$_5$ is consistent with chiral d-wave superconductivity with an angular dependence $f = e^{\pm i\phi} \cos(\chi)$. Therefore, the above approach will provide a basis to identify the many competing phases of the 115 compounds. Also, the phase diagrams for CeRh$_{1-x}$Co$_x$In$_5$ and CeRh$_{1-x}$Ir$_x$In$_5$ in Ref. [12] are of great interest for the perspective of the Gossamer superconductivity, i.e. a phase with competing order parameters [10,20,21]. We observe that (a) the incommensurate phases in both CeRh$_{1-x}$Co$_x$In$_5$ and CeRh$_{1-x}$Ir$_x$In$_5$ are conventional spin-density waves, (b) the commensurate phase in CeRh$_{1-x}$Co$_x$In$_5$ and the incommensurate+commensurate phase in CeRh$_{1-x}$Ir$_x$In$_5$ have d-wave symmetry. Therefore, there is a wide region where d-wave superconductivity coexists with unconventional nodal spin density wave order.

In summary, we have successfully applied a nodal weak-coupling BCS theory to fit recent experimental data on the directional thermal conductivity of CeRhIn$_5$. We find that in contrast to CeCoIn$_5$, which has plain d-wave order, this compound is consistent with chiral d-wave superconductivity. Furthermore, this technique will allow us to identify the many different phases which were recently discovered in doped derivatives of these materials.

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Fig. 3: Ratio of thermal conductivities of the $\vec{q}||c$ and $\vec{q}||\vec{a}$ direction, plotted as a function of $T/T_c$. The symbols represent the experimental data from Ref. [11].
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