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Field induced quasi-particles in the heavy-fermion superconductor $CeCoIn_5$

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Abstract

Heavy-fermion superconductor $CeCoIn_5$ has two energy scales for quasiparticle excitation mechanisms in the vortex state: Zeeman shift for the paramagnetic depairing and Doppler shift for the diamagnetic depairing. We have found the two energy-scales description of the specific heat in magnetic fields, which indicates the crossover of the quasiparticle excitation mechanisms from the diamagnetic depairing to the paramagnetic depairing. This result recalls careful interpretations about the field angle resolved specific heat experiment for identification of the superconducting gap structure.

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Since the discovery of its superconductivity, the heavy-fermion superconductor $CeCoIn_5$ ($T_c = 2.3\,K$) has generated extensive research activities [1]. Its superconductivity exhibits pronounced unconventional features. $CeCoIn_5$ exhibits the superconducting (SC) transition is of the first order at low temperatures, indicating a field-induced destruction of the SC state by Pauli paramagnetism [2,3]. The emergence of a Fulde–Ferrel–Larkin–Ovchinnikov SC state has also been reported in the vicinity of the upper critical field H_{c2} [4,5]. For its SC symmetry, a number of experimental studies of the SC state in $CeCoIn_5$ have revealed the existence of line nodes in the SC gap [6–8]. However, its pairing symmetry is still controversial. The four-fold anisotropy of the thermal conductivity and of the specific heat in magnetic fields suggests an order parameter with $d_{x^2-y^2}$ and d_{xy} symmetry, respectively [2,9]. This contradiction comes from the interpretation of the origin of the four-fold anisotropy in both quantities.

In order to identify the pairing symmetry, the intensive study of the quasiparticle (QP) excitation mechanisms by magnetic fields in the vortex state is currently of prime importance by specific heat measurements. Experimental results require two energy scales for the QP excitation mechanisms: the Zeeman shift for the paramagnetic depairing and the diamagnetic (orbital) depairing energy associated with the Doppler shift. In the heavy-fermion superconductor $CeCoIn_5$, the role of the Zeeman shift cannot be neglected. In this paper, we present the two energy-scales description of the specific heat in magnetic fields, which indicates the crossover of the QP excitation mechanisms from the diamagnetic depairing to the paramagnetic depairing.

Single crystals were prepared using an In self-flux method [1]. The sample was cut into a thin plate ($\sim 2.5 \times 2.3 \times 0.08\,mm^3$) with 2.6 mg and the largest plane oriented perpendicular to the c-axis. The directions of the tetragonal crystallographic axes of the sample were

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determined by X-ray Laue method. The field dependence of the specific heat was measured by a relaxation method with a dilution refrigerator [10].

Fig. 1 shows the field dependence of the electronic specific heat divided by temperature C_e/T at $T = 0.14$ K for $\boldsymbol{H}\|[1\,0\,0]$. The electronic specific heat $C_e = C - C_{sch}$ in magnetic fields was obtained after subtracting the nuclear Schottky contribution from the measured specific heat.

For $T/T_c < H/H_{c2}$ and $T/T_c, H/H_{c2} \ll 1$ ($T_c = 2.2$ K, $\mu_0 H_{c2} = 11.6$ T for $\boldsymbol{H}\|[1\,0\,0]$ [5]), the QPs induced by magnetic field are dominant. The QPs induced by magnetic fields have two origins: (i) *diamagnetic depairing* and (ii) *paramagnetic depairing*. For case (i), the QP energy spectrum $E_{\boldsymbol{k}}$ is affected and becomes $E'_{\boldsymbol{k}} = E_{\boldsymbol{k}} + \varepsilon_D$ by the Doppler shift $\varepsilon_D = \hbar\boldsymbol{k}\cdot\boldsymbol{v}_{rms}$ (diamagnetic depairing) in the mixed state, where $\boldsymbol{v}_s$ is the superfluid velocity around the vortices and $\hbar\boldsymbol{k}$ is the QP momentum. In the case of $\varepsilon_D \geqslant \Delta(\boldsymbol{k})$, this energy shift gives rise to a finite DOS at the Fermi level. This leads to the field dependence of $C_e/T \propto$ DOS being proportional to $\sqrt{H}$ at low temperature for the SC gap with line nodes [11]: $C_e/\gamma_N T \propto \varepsilon_D/\Delta_0$ at zero temperature, where $\varepsilon_D/\Delta_0 = (\pi\sqrt{2}/4)\sqrt{H/H_{orb}} \equiv b\sqrt{H/H_{c2}}$ is the energy scale associated with the Doppler shift [12]. H_{orb} is the orbital limiting field.

In magnetic field, for case (ii), the QP energy spectrum $E_{\boldsymbol{k}}$ splits and becomes $E'_{\boldsymbol{k}} = E_{\boldsymbol{k}} \pm \varepsilon_P$ by the Zeeman shift $\varepsilon_P = \mu H$ (paramagnetic depairing). The Zeeman shift destroys superconductivity over parts of the Fermi surface, where the ε_P exceeds the local gap $\Delta(\boldsymbol{k})$, and induces a spin polarization of the normal electrons: $C_e/\gamma_N T \propto \varepsilon_P/\Delta_0$ at low temperature for line node gap, where $\varepsilon_P/\Delta_0 = \sqrt{2}H/H_P \equiv cH/H_{c2}$ is the energy scale associated with the Zeeman shift [12–14]. H_P is the Pauli paramagnetic limiting field. The paramagnetic depairing in higher field leads to corrections of order H^2 to the average DOS. Now we modify the energy scale of the paramagnetic depairing to $\varepsilon_P/\Delta_0 = c\{H/H_{c2} + d(H/H_{c2})^2\}$. The field dependence of two energy scales ε_D and ε_P indicates that the diamagnetic and the paramagnetic depairings are dominant at low and relatively high fields, respectively.

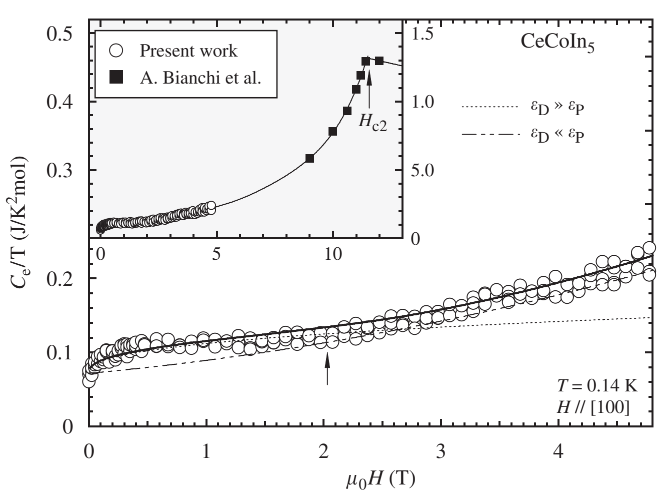

Fig. 1. Field dependence of C_e/T at $T = 0.14$ K for $\boldsymbol{H}\|[1\,0\,0]$. The line is a fit with the function in the text. Both dotted and dashed lines represent the limits of $\varepsilon_D \gg \varepsilon_P$ and $\varepsilon_D \ll \varepsilon_P$, respectively. The inset shows the field dependence of C_e/T at 0.14 K, which extrapolate to the upper critical field H_{c2} with high field experiment [5].

Recently, it has been shown that the field induced QP DOS at zero temperature should yield a relation with two energy scales [14]. To focus on the QP excitation only by magnetic field, we define $C_{QP}(T,H)/T \equiv C_e(T,H)/T - \gamma_0$. The scaling function has been explicitly calculated for the specific heat.

$$\frac{C_{QP}(0,H)}{C_{QP}(0,H_{c2})} = \frac{\varepsilon_D}{\Delta_0} f\left(\frac{\varepsilon_D}{\varepsilon_P}\right), \tag{1}$$

$$f(s) = \begin{cases} s + \frac{1}{2s} & (s \geq 1), \\ \frac{2}{\pi}\left(s + \frac{1}{2s}\right)\arcsin s + \frac{3}{\pi}\sqrt{1-s^2} & (s \leq 1), \end{cases} \tag{2}$$

where we estimate residual electronic-specific heat coefficient $\gamma_0 = 0.039$ J/K^2 mol and deduce $C_e(0,H_{c2})/T = 1.3$ J/K^2 mol in the inset of Fig. 1. The data at 0.14 K is chosen as the limit of $T/T_c \to 0$ because field induced QPs become dominant and C_e/T has little temperature dependence below 0.2 K: $C_{QP}(0,H)/T \simeq \{C_e(0.14,H) - C_e(0.14,0)\}/T$. C_{QP} is well fitted by two magnetic energy scales with $(b,c,d) = (0.065, 0.13, 2.4)$ in Fig. 1. We estimate the crossover field $H^* = 2.0$ T from $\varepsilon_D = \varepsilon_P$. Thus, unusual field dependence of specific heat of $CeCoIn_5$ is naturally explained with the crossover between the diamagnetic and the paramagnetic depairings [14,15]. Note that since the paramagnetic depairing has *no field orientation dependence*, the anisotropic DOS in magnetic fields by Doppler shift is weakened above H^* [14,12]. To identify the SC gap structure of $CeCoIn_5$, an intensive study by the field angle resolved specific heat experiment below H^* at low temperatures will be of importance.

In summary, we have found the two energy-scales description of the specific heat in magnetic fields, which reveals the crossover of the QP excitation mechanisms between the diamagnetic and the paramagnetic depairings. We also point out an influence on the field angle resolved specific heat experiment for determination of the SC gap structure.

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