Search for Superconducting Energy Gap in UPt₃ by Point-Contact Spectroscopy

Jun GOUCHI¹, Akihiko SUMIYAMA¹†, Akira YAMAGUCHI¹, Gaku MOTOYAMA², Noriaki KIMURA³, Etsuji YAMAMOTO⁴, Yoshinori HAGA⁴, Yoshichika ONUKI⁵

¹Graduate School of Material Science, University of Hyogo, Hyogo 678-1297, Japan
²Department of Material Science, Shimane University, Matsue 690-8504, Japan
³Center for Low Temperature Science, Tohoku University, Sendai 980-8578, Japan
⁴Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan
⁵Department of Physics and Earth Sciences, University of the Ryukyus, Nishihara, Okinawa 903-0213, Japan

E-mail: †sumiyama@sci.u-hyogo.ac.jp

Abstract. We have investigated the differential resistance of the point contacts between heavy-fermion superconductor UPt₃ and a normal metal Pt, which were fabricated using a commercial piezo-electric actuator, and retried the observation of the energy gap of UPt₃. A V-shaped dip is observed in both normal and superconducting states and disappeared around T_K ~ 20 K, suggesting that it is related to the Kondo effect. Below the superconducting transition temperature, a shallow double-minimum structure, which indicates the energy gap, has been observed for the contacts on the faces perpendicular to the a-, b- and c-axes of UPt₃.

1. Introduction

The heavy-fermion superconductor UPt₃ is one of the candidates for unconventional superconductors, because the temperature dependence of various physical properties, such as specific heat[1], NMR relaxation rate[2] and ultrasound attenuation[3], shows a power law behavior suggesting a gap function vanishing on the Fermi surface. Its remarkable feature is complex field-temperature( H-T) phase diagram[4]. In order to explain these results comprehensively, various candidates have been proposed for the odd-parity order parameter described by the d vector: \( \hat{\Delta} (\mathbf{k}) = i (d_x \sigma_x + d_y \sigma_y + d_z \sigma_z) \). At present, two favorable candidates are \( E_{2_u} \): d(\mathbf{k}) \sim (k_a + i k_b) \sigma_y \) and \( E_{1_u} \): d(\mathbf{k}) \sim (k_a \hat{b} + k_b \hat{c}) (5k_c^2 - 1) [6, 7] scenarios. Recently, we have investigated the Josephson effect between UPt₃ and an s-wave superconductor Al for the a-, b- and c--axes junctions, and found that the results support the \( E_{1_u} \) scenario[8].

Point-Contact Spectroscopy(PCS) is one of the tunneling phenomena and gives fruitful information on the magnitude of the energy gap for conventional superconductors[9]. For unconventional superconductors, the sign change of the order parameter causes the formation of zero energy Andreev bound state at the surface, when injected and reflected quasiparticles feel different signs of the pair potential. In the earlier investigation by Goll et al.[10, 11] and Obermair et al.[12], the double minimum structure, which is a sign of the energy gap, was observed for the current flow parallel to the c-axis (I \( \parallel \) c), but not for I \( \perp \) c. This anisotropy...
Figure 1. (Color online) Photographs of (a) UPt$_3$ single crystal and (b) experimental set up was ascribed to the point node on the pole and the line node on the basal plane in the $E_{2u}$ scenario. However, there is no line node on the equator in the $E_{1u}$ scenario and the energy gap may be observed for $I \perp c$. In this report, we have retried to observe the energy gap using UPt$_3$-Pt point-contacts.

2. Experimental Procedure
The single crystal of UPt$_3$ has been grown by the Czochralski-pulling method in a tetra-arc furnace. The residual resistivity ratio was above 500, indicating the high quality of the sample. The upper and lower superconducting transition temperatures were $T_c^+ \sim 0.58$ K and $T_c^- \sim 0.53$ K, respectively[13]. The crystal was cut to the shape that has faces perpendicular to the $a[11\bar{2}0]$, $b[10\bar{1}0]$ and $c[0001]$ axes, as shown Fig.1(a). The sample surface was not polished; The faces perpendicular to the $a$- and $b$-axes were as-grown surface and that perpendicular to the $c$-axis was a cleaved plane.

We have used two commercial piezo-electric actuators (the positioner: attocube ANPx101/RES and the rotator: attocube ANRv51/res); both actuators have the resistance encoder as shown Fig.1(b). The UPt$_3$ sample and a normal metal needle (Pt) were set to the rotator and positioner, respectively. A Pt needle was pressed onto the sample with the positioner. In addition, we can perform the angle resolved PCS by rotating UPt$_3$. Hereafter, we denote the contacts as $I \parallel a$, $I \parallel b$ and $I \parallel c$ on the assumption that the current flow is perpendicular to the surface. The point-contact apparatus was set to the mixing chamber of a dilution refrigerator and cooled down to 50mK. For the measurements at higher temperatures ($T > 4.2$K), the apparatus was set to the probe in a glass dewer and cooled by liquid He. The PCS was measured using the “differential conductance mode” of the combination of a current source (Keithley 6221) and a nano voltmeter (Keithley 2182).

3. Result and Discussion
Figure 2 shows the temperature dependence of $dV/dI$ vs. $V$ characteristics for $I \parallel a$, $I \parallel b$ and $I \parallel c$. The contact resistance $R_0$ at zero bias is approximately the sum of the Sharvin resistance $R_{SHA}$ and the Maxwell resistance $R_{MAX}$, as given by

$$R_0 \sim R_{SHA} + R_{MAX} = \frac{2R_k}{(dk_F)^2} + \frac{\rho}{4d},$$

where $k_F$ is the Fermi wave number, $R_k = h/e^2 = 25.8k\Omega$, $d$ is the radius of the contact between UPt$_3$ and Pt, and $\rho$ is the electrical resistivity of UPt$_3$ near the contact[9]. The $R_{SHA}$ and $R_{MAX}$ values calculated using eq. (1) are listed in Table 1. When $R_{SHA}$ is dominant,
Table 1. Various resistances of UPt$_3$-Pt point contacts. $R_0$, $R_{SHA}$ and $R_{MAX}$ are zero-bias, Sharvin and Maxwell resistances, respectively, while $d$ is the radius of the contact. A typical Fermi wave number $k_F \sim 10 \text{ nm}^{-1}$, electrical resistivity $\rho(0.7 \text{ K}) \sim 1 \mu\Omega\text{cm}$ for $I \parallel c$, $\rho(0.7 \text{ K}) \sim 0.5 \mu\Omega\text{cm}$ for $I \perp c$ and $\rho(4.2 \text{ K}) \sim 7.7 \mu\Omega\text{cm}$ for $I \parallel c$ are used for calculation[13].

|                  | $I \parallel a(0.7 \text{ K})$ | $I \parallel b(0.61 \text{ K})$ | $I \parallel c(0.64 \text{ K})$ | Contact A(4.2 K) | Contact B(4.2 K) |
|------------------|---------------------------------|---------------------------------|---------------------------------|------------------|------------------|
| $R_0(\Omega)$    | 15.97                           | 2.53                            | 2.34                            | 2.4              | 5.2              |
| $R_{SHA}(\Omega)$| 15.54                           | 2.36                            | 2.26                            | 1.38             | 3.79             |
| $R_{MAX}(\Omega)$| 0.43                            | 0.17                            | 0.08                            | 1.02             | 1.41             |
| $d(\text{nm})$   | 5.8                             | 14.8                            | 15.1                            | 19.3             | 11.6             |

Figure 2. (Color online) Temperature dependence of $dV/dI$ vs. $V$ characteristics for (a) $I \parallel a$, (b) $I \parallel b$ and (c) $I \parallel c$. The spectra are shifted vertically for clarity by 0.04 $\Omega$, 0.02 $\Omega$ and 0.01 $\Omega$ for $I \parallel a$, $I \parallel b$ and $I \parallel c$, respectively.

The contact is in the ballistic limit and the information on the electronic density of states is obtained. Compared with the earlier investigation[10, 11, 12], $R_0$ in our contacts is one order of magnitude larger, which means that the contact approaches the ballistic limit. When UPt$_3$ becomes superconducting, $R_0$ decreases very little, while a double minimum structure, which is a sign of the energy gap, appears at low temperatures. A V-shaped dip structure, on the other hand, was observed in both normal and superconducting states. The origin of this structure will be discussed below. Since the double minimum structure is vague, the spectra are separated into the symmetric and asymmetric components to clarify the formation of the energy gap, as given by

\[
\left( \frac{dV}{dI} \right)_{\text{sym}} = \frac{1}{2} \left[ \frac{dV}{dI}(+V) + \frac{dV}{dI}(-V) \right], \quad \left( \frac{dV}{dI} \right)_{\text{asym}} = \frac{1}{2} \left[ \frac{dV}{dI}(+V) - \frac{dV}{dI}(-V) \right].
\]
The symmetric component reflects the density of states at the Fermi energy, while the asymmetric component may be ascribed to the Seebeck effect or the Fano effect.

Figures 3 (a) and (b) show the temperature dependence of the symmetric and asymmetric components for $I \parallel a$. The double minimum structure was observed obviously below $T_c$, while the temperature dependence of the asymmetric component does not change. As shown in Figs. 3(c) and (d), similar behaviors have been observed also for $I \parallel b$ and $I \parallel c$. Since the V-shaped dip structure in the background prevents fitting the spectra to Blonder-Tinkham-Klapwijk (BTK) formula[14] to estimate the superconducting energy gap $2\Delta$ was defined as the width of the double minimum structure. The obtained value $\Delta \sim 0.5$ meV for the three directions is larger than the BCS gap function $\Delta = 1.76k_BT_c \sim 0.088$ meV with $T_c \sim 0.58$ K. Our result is larger than the reported values: 0.039 meV[10] and 0.058 meV[11]. One possible explanation of observing a larger energy gap than the true value is that only a part of the voltage drop exists at the boundary between superconducting UPt$_3$ and the normal metal, and the rest is in the normal metal: Pt and possibly some UPt$_3$ part that remains normal. This explanation, however, is questionable, since the three contacts give a similar energy gap $\sim 0.5$ meV notwithstanding the large difference of $R_0$: 16 $\Omega (I \parallel a)$ and 2 $\Omega (I \parallel b, I \parallel c)$. If the true smaller gap values are also similar, the ratio of resistance between the boundary and the normal metal needs to coincide among the contacts in spite of different $R_0$ values. The discrepancy of the energy gap values determined by PCS is still left unsettled. It should be noted that such a large energy gap is also reported for URu$_2$Si$_2$: $\Delta$ is approximately 0.7 meV, while $\Delta = 1.76k_BT_c \sim 0.27$ meV[15].

The present observation of the double minimum structure for $I \parallel a$ and $I \parallel b$ raises a question to the interpretation in the earlier report that the absence of it is caused by the line node in the basal plane in the $E_{2u}$ order parameter[16]. In order to decide the validity of the two scenarios by the point-contact spectra, the comparison with the detailed calculation that takes into account the current injection other than the normal direction will be needed.

Figures 4(a) and (b) show the temperature dependence of $dV/dI$ vs. $V$ for $I \parallel c$ above 4.2 K. As the temperature is increased, $R_0$ increases rapidly, while the V-shaped dip structure becomes
Figure 4. (Color online) Temperature dependence of dV/dI vs. V characteristics above 4.2 K for (a) Contact A and (b) Contact B.

Shallow and disappears at about 15 ∼ 20 K. This temperature almost coincides with the Kondo temperature, where the increasing rate of bulk resistivity $\rho$ with raising temperatures begins to decrease. The increase of $R_0$ is explained by that of the Maxwell resistance; when the $d$ value in Table 1 is used, the ratio $\rho(15 \text{ K})/\rho(4.2 \text{ K}) \sim 4.7$[13] leads to the increase of the Maxwell resistance $R_{\text{MAX}}(15 \text{ K}) - R_{\text{MAX}}(4.2 \text{ K}) \sim 3.8 \Omega$ for Contact A and 5.2 Ω for Contact B, which are nearly the observed change in $R_0$.

Since the Maxwell resistance exceeds the Sharvin resistance at 7.2 K(Contact A) and 10 K(Contact B) according to eq. (1), the contact changes its behavior from the ballistic regime to the diffusive and then the thermal regime, and the spectra less reflect the electronic states of UPt$_3$[9]. The V-shaped dip structure observed from the ballistic regime probably reflects the peak of the electronic density of states at the Fermi energy caused by the Kondo effect (Kondo peak), while the disappearance of it may be ascribed to the reduction of the Kondo peak above the Kondo temperature or the change in $R_{\text{MAX}}$ by local heating in the thermal regime.

The voltage dependence of dV/dI in the thermal regime is interpreted by the temperature dependence of $\rho$; Joule heating of the contact region yields a hot spot with maximum temperature $T_{\text{PC}}$ given by

$$T_{\text{PC}} = \sqrt{T_{\text{bath}}^2 + V^2/4L},$$

where $T_{\text{bath}}$ is the bath temperature, $V$ is the applied voltage and $L$ is the Lorenz number[9]. At $V = 4 \text{ mV}$, $T_{\text{PC}} \sim 14 \text{ K}$ when $T_{\text{bath}} \sim 4.2 \text{ K}$, and $T_{\text{PC}} \sim 20 \text{ K}$ when $T_{\text{bath}} \sim 15 \text{ K}$. When $\rho(14 \text{ K})/\rho(4.2 \text{ K}) \sim 4.3$, $\rho(20 \text{ K})/\rho(15 \text{ K}) \sim 1.3$[13] and the $d$ value in Table 1 are used, this heating leads to the increase of $R_{\text{MAX}}$ between $V = 0$ and 4 mV by 3.3 Ω at 4.2 K and 1.4 Ω at 15 K for Contact A, while 4.7 Ω at 4.2 K and 2 Ω at 15 K for Contact B. Although the local heating and the temperature dependence of $\rho$ explain the reduction of the spectra at least qualitatively, the estimated increase below 4mV is far larger than the observed values for Contact B. This discrepancy may suggest that the present contacts are still in the diffusive regime below 20 K and the spectra reflect the electronic density of states. It should be noted that the previous works on the PCS of UPt$_3$ in the normal state[16, 17, 18], which were explained by the Joule
heating, were on the spectra up to 30 mV, where the heating should be crucial.

4. Summary
In summary, we have investigated the point-contact spectroscopy between UPt$_3$ and Pt. In the case of superconducting state, we have observed the double minimum structure in d$V$/d$I$ vs. $V$ characteristics, which is a sign of the energy gap, for $I \parallel a$, $I \parallel b$ and $I \parallel c$. In both normal and superconducting states, the V-shaped dip has been observed up to $T \sim 20$ K, which is related to the Kondo effect in UPt$_3$.

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