Vortex lattice melting in the ultraclean heavy-fermion superconductor URu$_2$Si$_2$

R Okazaki$^1$, Y Kasahara$^{1,7}$, H Shishido$^1$, M Konczykowski$^2$, K Behnia$^3$, Y Haga$^4$, T D Matsuda$^4$, Y Onuki$^{4,5}$, T Shibauchi$^1$ and Y Matsuda$^{1,6}$

$^1$ Department of Physics, Kyoto University, Kyoto 606-8502, Japan
$^2$ Laboratorie des Solides Irradiés, CNRS-UMR 7642 and CEA/DSM/DRECAM, Ecole Polytechnique, 91128, Palaiseau, France
$^3$ Laboratoire de physique quantique (CNRS), ESPCI, 10 Rue Vauquelin, 75005 Paris, France
$^4$ Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan
$^5$ Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan
$^6$ Institute for Solid State Physics, University of Tokyo, Kashiwanoha, Kashiwa, Chiba 277-8581, Japan

E-mail: okazaki@scphys.kyoto-u.ac.jp

Abstract. The vortex states and the quasiparticle dynamics in the ultraclean heavy-fermion superconductor URu$_2$Si$_2$ ($T_c=1.45$ K) are studied by the electronic and thermal transport measurements. We find that a distinct vortex lattice melting transition, which is similar to that in high-$T_c$ cuprates, occurs well below the mean-field upper critical field. The thermal fluctuations are exceptionally enhanced by very low carrier number with heavy mass even at sub-Kelvin temperatures. Additionally, we find a thermal conductivity anomaly below the melting transition, indicating enhancement of the quasiparticle mean free path possibly due to the formation of a novel quasiparticle Bloch state.

1. Introduction
Since the discovery of the heavy-fermion superconductor URu$_2$Si$_2$ [1], the “hidden order” phase ($T_h=17.5$ K), where most of the carriers disappear and the order parameter is still unknown, has attracted much interest and the superconducting state ($T_c=1.45$ K) coexisting with the hidden order phase is also revealed to be highly unusual [2].

In this paper, we report the vortex lattice melting in ultraclean URu$_2$Si$_2$, which has been observed in high-$T_c$ cuprates, caused by large thermal fluctuations due to the small carrier number with heavy mass despite the low $T_c$. The melting transition is directly manifested by sharp resistivity drops, while the existence of an irreversibility line below the upper critical field has been suggested by the magnetic susceptibility measurements [3]. We also observe an unexpected enhancement of the quasiparticle (QP) mean free path below the melting transition, which implies that the QPs are scattered less by the vortex lattice than liquid due to the formation of a novel Bloch-like state by the periodic vortex lattice [4].

$^7$ Present address : Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
2. Experimental

Extremely clean single crystals of URu$_2$Si$_2$ were grown by the technique described elsewhere [5]. The exceptionally low residual resistivity $\rho_0$ and large residual resistivity ratio $RRR = 670$ attest the highest crystal quality currently achievable. The ac-resistivity was measured in a $^3$He cryostat by the standard four-probe method. The thermal conductivity $\kappa$ was measured in a dilution refrigerator by a standard four-wire steady state method.

3. Results and discussion

We show the temperature dependence of the resistivity in Figs. 1 (a) and (b). In magnetic fields, the resistivity exhibits very sharp drop, which is even sharper than the transition width in zero field. The temperatures determined by the peak positions of $d\rho/dT$ (insets of Fig. 1 (a) and (b)) are denoted by $T_m$ and are marked by solid arrows.

The thermal conductivity shown in Fig. 2 gives important information on the vortex state. In zero field, $\kappa/T$ increase with decreasing $T$. Here the electronic heat conduction is described by $\kappa/T \sim N(0)v_F\ell$, where $N(0)$, $v_F$, and $\ell$ are the QP density of states, Fermi velocity, and QP mean free path, respectively. The enhancement of $\kappa/T$ below $T_{\sigma_0}$ is caused by an enhancement of $\ell$ due to the formation of gap, which overcomes the reduction of $N(0)$ in the superconducting state, as observed in several strongly correlated electron systems [6]. The behavior of $\kappa/T(T)$ changes dramatically in magnetic fields as shown in Figs. 2 (b) and (c). With decreasing $T$, $\kappa/T$ begins to decrease with a distinct cusp, as marked by dotted arrows. Recent theories show that thermal conductivity has no fluctuation correction [7, 8], and therefore it is natural to regard the cusp temperature of $\kappa/T$ as the mean-field transition temperature $T_c(H)$. Further decrease of the temperature leads to a second anomaly below which $\kappa/T$ turns to increase from that extrapolated from high temperatures. This second anomaly is located very close to $T_m$, as marked by solid arrows, indicating that the QP transport is dramatically changed at $\sim T_m$, which will be discussed later.

We show the mean-field transition temperature $T_c$ determined by the thermal conductivity by dotted arrows in Figs. 1. It is obvious that $T_c$ is well above $T_m$. The feature of the resistive transition of URu$_2$Si$_2$ bears striking resemblance to that of clean YBa$_2$Cu$_3$O$_7$, where the sharp

![Figure 1](image.png)

**Figure 1.** Temperature dependence of the resistivity for (a) $H \parallel a$ and (b) $H \parallel c$. The solid and dotted arrows indicate the melting temperature $T_m$ and the mean-field transition temperature $T_c$, respectively. The insets show $d\rho/dT$ as a function of $T$. The data are vertically shifted.
A drop of the resistivity is observed in a linear scale at the melting transition with no anomaly at \( T_c(H) \) \cite{9}. We therefore conclude that the melting transition takes place at \( T_m \). It should be noted that the anomaly in the thermal conductivity around \( T_m \) is consistent with the melting transition, which should change the QP transport.

Here we discuss the origin of the thermal melting transition in URu$_2$Si$_2$. The fundamental parameter which represents the order of the thermal fluctuations is the Ginzburg number, \( G_i = \left[ k_B T_c / H_c(0)^2 \xi_{ab}^3 \right]^{\frac{1}{2}} / 2 \), which is the ratio of the condensation energy within the coherence volume and the thermal energy \( k_B T_c \) \cite{10}. Here \( H_c = \Phi_0 / 2 \sqrt{2 \pi \lambda_{ab} \xi_{ab}} \) is the thermodynamic critical field, \( \lambda_{ab} \) and \( \xi_{ab} \) are penetration and coherence lengths in the ab-plane at \( T = 0 \) K, respectively. Let us examine the difference between URu$_2$Si$_2$ and the other system quantitatively. In conventional low-\( T_c \) superconductors, \( G_i \) ranges from \( 10^{-11} \) to \( 10^{-7} \), while in YBa$_2$Cu$_3$O$_7 \ G_i \) takes \( \sim 10^{-2} \) \cite{10}. Owing to the lower carrier density and a large mass, the penetration depth of URu$_2$Si$_2$ becomes very long \cite{11}, which gives rise to a large \( G_i \) value \( G_i \sim 3 \times 10^{-4} \). These results

![Figure 2](image1.png)

**Figure 2.** Temperature dependence of the thermal conductivity divided by temperature \( \kappa/T \) (left axis) and the resistivity (right axis) in (a) zero, (b) 1 T, and (c) 2 T fields.

![Figure 3](image2.png)

**Figure 3.** \( H - T \) phase diagram of URu$_2$Si$_2$ for (a) \( H \parallel a \) and (b) \( H \parallel c \).
lead us to conclude that the exceptionally large thermal fluctuations melt the vortex lattice in URu$_2$Si$_2$ even at sub-Kelvin temperatures. In Figs. 3, we show the $H - T$ phase diagram of URu$_2$Si$_2$ determined by the present study. The large $G_t$ value also results in the reduction of $H_m$, extending the vortex liquid region.

In addition to the remarkable vortex matter physics, the present ultraclean system provides an important information of the QP transport in the vortex state, which has been a controversial issue [12, 13]. The QP scattering is caused by Andreev scattering on the velocity field associated with the vortices, and a single vortex acts as a strong scattering center. The QP mean free path in the present ultraclean URu$_2$Si$_2$ well exceeds 1 $\mu$m [5], which is two orders magnitude longer than the inter-vortex distance at $\mu_0H = 1$ T. Such a long QP mean free path would not be influenced by the change of the vortex structure owing to the melting transition, but nevertheless we observed the enhancement below $T_m$. A possible explanation for this unusual enhancement is that the nearly perfect vortex lattice is formed below $T_m$, and low energy QPs are described by Bloch wave function and are less scattered in that periodic lattice [14, 15]. We note that this enhancement of the thermal conductivity in the vortex solid state has never been observed even in very clean YBa$_2$Cu$_3$O$_7$ [16], implying that ultraclean system is required for the formation of the QP Bloch state.

4. Summary

In summary, we measured the transport and thermodynamic properties in URu$_2$Si$_2$ and show strong evidence of the thermal melting transition at sub-Kelvin temperatures. The periodic vortex lattice is suggested to form the QP Bloch state with long mean free path. The present results provide new insights on vortex matter physics as well as QP dynamics in the vortex state of type-II superconductors.

Acknowledgments

We thank R. Ikeda, T. Kita, N. Kokubo, K. Machida, T. Nishizaki, Z. Tešanović, and I. Vekhter for discussions. This work is supported by Grants-in-Aid for Scientific Research from the Japan Society for the Promotion of Science.

References

[1] Palstra T T M, Menovsky A A, van den Berg J, Dirkmaat A J, Kes P H, Nieuwenhuys G J and Mydosh J A 1985 Phys. Rev. Lett. 55 2727

[2] Kasahara Y, Iwasawa T, Shishido H, Shibauchi T, Behnia K, Haga Y, Matsuda T D, Onuki Y, Sigrist M and Matsuda Y 2007 Phys. Rev. Lett. 99 116402

[3] Visani P, Dalichaouch Y, Lopez de la Torre M A, Lee B W, Seaman C L and Maple M B 1994 Phys. Rev. B 49 4376

[4]Okazaki R, Kasahara Y, Shishido H, Konczykowski M, Behnia K, Haga Y, Matsuda T D, Onuki Y, Shibauchi T and Matsuda Y 2008 Phys. Rev. Lett. 100 037004

[5]Ohkuni H et al 1999 Philo. Mag. B 79 1045

[6]Kasahara Y, Shimono Y, Shibauchi T, Matsuda Y, Yonezawa S, Muraoka Y and Hiroi Z 2006 Phys. Rev. Lett. 96 247004

[7]Niven D R and Smith R A 2002 Phys. Rev. B 66 214505

[8]Vishveshwara S and Fisher M P A 2001 Phys. Rev. B 64 134507

[9]Kwok W K, Flesher S, Welp U, Vinokur V M, Downey J, Crabtree G W and Miller M M 1992 Phys. Rev. Lett. 69 3370

[10] Blatter G, Gefel’dman M V, Geshkenbein V B, Larkin A I and Vinokur V M, 1994 Rev. Mod. Phys. 66 1125

[11] Amato A 1997 Rev. Mod. Phys. 69 1119

[12] Matsuda Y, Iwasa K and Vekhter I 2006 J. Phys.: Condens. Matter 18 R705

[13] Vekhter I and Houghton A 1999 Phys. Rev. Lett. 83 4626

[14] Franz M and Tešanović Z 2000 Phys. Rev. Lett. 84 554

[15] Yasui K and Kita T 1999 Phys. Rev. Lett. 83 4168

[16] Ocana R, Taldenkov A, Esquinazi P and Kopecleviž Y 2001 J. Low Temp. Phys. 123 181