

# UC Irvine

## UC Irvine Previously Published Works

### Title

Evidence for unconventional superconductivity in single crystals of the antiferromagnetic heavy-electron compound URu<sub>2</sub>Si<sub>2</sub>

### Permalink

<https://escholarship.org/uc/item/1jv2k4b0>

### Journal

Physica B: Physics of Condensed Matter, 171(1-4)

### ISSN

0921-4526

### Authors

Maple, MB  
Dalichaouch, Y  
Lee, BW  
[et al.](#)

### Publication Date

1991-05-01

### DOI

10.1016/0921-4526(91)90519-K

### Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

# Evidence for unconventional superconductivity in single crystals of the antiferromagnetic heavy-electron compound URu<sub>2</sub>Si<sub>2</sub>

M.B. Maple<sup>a</sup>, Y. Dalichaouch<sup>a</sup>, B.W. Lee<sup>a</sup>, C.L. Seaman<sup>a</sup>, P.K. Tsai<sup>a</sup>, P.E. Armstrong<sup>b</sup>, Z. Fisk<sup>b</sup>, C. Rossel<sup>c</sup> and M.S. Torikachvili<sup>d</sup>

<sup>a</sup>Department of Physics and Institute for Pure and Applied Physical Sciences, University of California, San Diego, La Jolla, CA 92093, USA

<sup>b</sup>Los Alamos National Laboratory, Los Alamos, NM 87545, USA

<sup>c</sup>IBM Zürich Research Laboratory, Saumerstrasse 4, CH-8803 Rushlikon, Switzerland

<sup>d</sup>Department of Physics, San Diego State University, San Diego, CA 92182, USA

Invited paper.

Specific heat  $C(T)$  and upper critical field  $H_{c2}(T)$  measurements have been performed on two single crystal specimens (denoted A and B) of the antiferromagnetic heavy-electron superconductor URu<sub>2</sub>Si<sub>2</sub>. Specific heat measurements on both single crystals reveal two distinct jumps, indicative of two superconducting phases. This is reminiscent of the antiferromagnetic heavy-electron compound UPt<sub>3</sub> in which multiple superconducting transitions have been observed and attributed to coupled antiferromagnetic and multicomponent superconducting order parameters, although two superconducting phases associated with two different states of the crystal cannot be ruled out. The relative magnitudes of the two specific heat jumps observed in crystal B suggest that the two superconducting phases occupy nearly equal volume fractions of the crystal. At temperatures below the lower jump, the specific heat of both crystals can be described by  $C_s(T) = \gamma_s(0)T + AT^3$  with  $\gamma_s(0) \approx 0.5\gamma_n(0)$ , where  $\gamma_n(0)$  is the value of the normal-state electronic specific heat coefficient  $\gamma_n(T)$ , extrapolated to  $T=0$ . The two critical temperatures inferred from the specific heat jumps in crystal B, measured in magnetic fields  $H$  between 0 and 15 kOe applied parallel to the  $c$ -axis, have a similar dependence on  $H$ . Resistive measurements of  $H_{c2}(T)$  on specimens from crystal A between 0 and 60 kOe reveal a kink near 2 kOe for  $H\parallel c$  and strong positive curvature in  $H_{c2}(T)$  below  $\sim 3$  kOe for  $H\parallel a$ .

## 1. Introduction

The heavy-electron superconductors CeCu<sub>2</sub>Si<sub>2</sub> [1], UBe<sub>13</sub> [2], UPt<sub>3</sub> [3], and URu<sub>2</sub>Si<sub>2</sub> [4–6] have attracted considerable attention because of the possibility that they exhibit an unconventional type of superconductivity involving novel types of pairing and/or pairing mechanisms [7]. Especially interesting are the three U heavy-electron superconductors. Although UBe<sub>13</sub>, UPt<sub>3</sub>, and URu<sub>2</sub>Si<sub>2</sub> have different crystal structures (cubic, hexagonal, and tetragonal, respectively) and electron effective masses  $m^*$  ( $\sim 300m_e$  [8],  $\sim 200m_e$  [9], and  $\sim 25m_e$  [5], respectively), common physical characteristics appear to be emerging which illustrate the intimate relationship between superconductivity and magnetism and may

provide a basis for developing a fundamental understanding of superconductivity in these remarkable materials. These characteristics include the occurrence of antiferromagnetic ordering with a small magnetic moment  $\mu$  of a few hundredths of a Bohr magneton below a Néel temperature  $T_N \approx 10T_c$ , where  $T_c$  is the superconducting critical temperature, and the destruction of superconductivity accompanied by the appearance of magnetic order with a much larger magnetic moment of several tenths of a Bohr magneton upon substituting another element. Evidence for antiferromagnetic ordering in UBe<sub>13</sub> ( $T_c \approx 0.9$  K) at  $T_N \approx 8.8$  K, based upon thermal expansion measurements, was recently reported [10], but remains to be confirmed by  $\mu$ SR or neutron scattering measurements. Neutron scat-

tering experiments [11] on UPt<sub>3</sub> ( $T_c \approx 0.5$  K) indicate antiferromagnetic ordering below  $T_N \approx 5.5$  K with  $\mu \approx 0.02 \mu_B/\text{U-atom}$ , while various measurements [4–6, 12–14] on URu<sub>2</sub>Si<sub>2</sub> ( $T_c \approx 1.4$  K) reveal antiferromagnetic ordering with  $T_N \approx 17.5$  K and  $\mu \approx 0.03 \mu_B/\text{U-atom}$ . Superconductivity is suppressed and replaced by localized moment antiferromagnetism upon substitution of Th for U or Pd for Pt [15–17] in UPt<sub>3</sub> and Rh for Ru [18] in URu<sub>2</sub>Si<sub>2</sub>, and local moment ferromagnetism with  $\mu \approx (0.4\text{--}0.6)\mu_B/\text{U-atom}$  upon substitution of Tc or Re for Ru [19] in URu<sub>2</sub>Si<sub>2</sub>.

One of the most striking recent developments is the apparent occurrence of two or more distinct superconducting phases in  $(\text{U}_{1-x}\text{Th}_x)\text{Be}_{13}$  as a function of Th composition  $x$  [20] as revealed by high-pressure experiments [21] and in UPt<sub>3</sub> in the  $H$ – $T$  plane [22–24]. The case of UPt<sub>3</sub> has been studied extensively and is the subject of several theoretical investigations in which the multiple superconducting transitions have been attributed to coupled antiferromagnetic and multicomponent superconducting order parameters [25, 26]. In this paper, we report specific heat and upper critical field measurements on single crystal specimens of the antiferromagnetic heavy-electron superconductor URu<sub>2</sub>Si<sub>2</sub> which show features in the specific heat  $C(T, H)$  and upper critical field  $H_{c2}(T)$  curves which are indicative of unconventional superconductivity.

## 2. Experimental details

Two single crystals of URu<sub>2</sub>Si<sub>2</sub> (denoted A and B) were prepared from arc-cast polycrystalline rods by zone-melting in a high vacuum. Laue X-ray diffraction analysis was used to orient the crystallites from which specimens for the specific heat and upper critical field measurements were cleaved and cut with a diamond wheel saw. Specific heat measurements as a function of temperature in magnetic fields up to 15 kOe applied parallel to the  $c$ -axis were made in a <sup>3</sup>He calorimeter using the heat-pulse technique. Resistive upper critical field  $H_{c2}(T)$  measurements for two orientations of the applied

magnetic field  $H$ ,  $H\parallel c$  and  $H\parallel a$ , were made on two rectangular parallelepiped-shaped specimens from sample A in a <sup>3</sup>He–<sup>4</sup>He dilution refrigerator in fields up to 60 kOe and temperatures down to 0.15 K using a four-wire bridge. The 16 Hz AC measuring currents of  $\sim 10$  and  $\sim 1$  mA/cm<sup>2</sup> were directed along the  $a$ -axis for the measurements with  $H\parallel c$  and  $H\parallel a$ , respectively.

Back-scattered Laue X-ray diffraction, electron microprobe analysis, and scanning electron microscopy SEM were performed on crystal B in order to establish that it is a single crystal of uniform composition. Crystal B was cleaved from the zone-melted rod; the  $c$ -axis, which is perpendicular to the shiny, layered surfaces of the cleaved ends, is oriented at an angle of  $\sim 22^\circ$  with the axis of the rod, as verified by Laue diffraction patterns. Laue photographs were taken at numerous locations on the surface of the crystal including the cleaved ends, and each displayed well-resolved diffraction spots. The mutual symmetry of the spots from different locations is consistent with constant crystallographic orientation everywhere on the surface. The preservation of the crystal structure over the entire surface strongly suggests that the sample is one single crystal throughout the bulk. SEM performed on a cleaved and polished surface of crystal B revealed no evidence of multiple or impurity phases, and no features down to the micron scale, indicating that the specimen is very uniform in morphology and chemical composition.

It has been suggested that Si deficiency could be responsible for the wide range of  $T_c$  values measured for different URu<sub>2</sub>Si<sub>2</sub> specimens. Any Si inhomogeneity in one crystal might thereby create a range of  $T_c$  values which would be expected to broaden the superconducting jump(s) in the specific heat. We have measured the composition ratio of U : Ru : Si at several locations on each cleaved side of crystal B by electron microprobe analysis using a submicron beam size. The experimental uncertainty of this technique, obtained by repeated measurements at the same location, is estimated to be  $\sim \pm 0.5\%$ . On one side, the Si : U and Ru : U ratios

were both found to be constant within a standard deviation  $\sigma = 0.5\%$ . The other side showed a variation in the Si : U ratio of  $\sigma \approx 2\%$ , except for several locations near the edge of the cleaved face which deviated by at most  $\approx 4\%$ , while the Ru : U ratio was constant. We estimate the Si and Ru contents of the two sides to be within 2% of each other. The effect such a variation in Si content has on  $T_c$  remains to be established.

### 3. Results and discussion

Displayed in fig. 1 are zero-field  $C$  versus  $T$  data between  $\sim 0.5$  K and 2 K for the two URu<sub>2</sub>Si<sub>2</sub> single-crystal specimens (denoted A and B). There are two features in the  $C(T)$  data for specimen A which suggest the presence of two superconducting transitions: one at  $T_{c1} \approx 1.3$  K which occupies most of the sample volume and another at  $T_{c2} \approx 1.2$  K, which occupies a small fraction of the sample volume. The  $C(T)$  data for sample B also exhibit two features which are indicative of two superconducting transitions, one at  $T_{c1} \approx 1.3$  K and the other at  $T_{c2} \approx 1.0$  K, which occupy about equal fractions of the sample volume. There is no obvious feature in the  $C(T)$  data for sample B at  $T \approx 1.2$  K. Taken at face value, the  $C(T)$  data in fig. 1 for samples A and B suggest the presence of two superconducting

transitions in each sample which are separated by  $\sim 0.1$  K in sample A and  $\sim 0.3$  K in sample B. The volume fractions of the superconducting phases and the temperature interval between them appear to depend sensitively on the state of the samples (e.g., strains, impurities, disorder, etc.). This may explain why  $C(T)$  data [8] previously reported in polycrystalline samples of URu<sub>2</sub>Si<sub>2</sub> generally display a broad feature indicative of a continuous distribution of  $T_c$ s in the range  $\sim (1.0-1.4)$  K, rather than the sharper features at the multiple  $T_c$ s observed in the single crystals reported here. Presumably, the less strained and more highly ordered state of the single crystal specimens allows the multiple superconducting transitions to be resolved in the  $C(T)$  data. A similar situation was encountered for UPt<sub>3</sub>, where specific heat measurements on polycrystalline samples revealed a broad feature indicative of a continuous distribution of  $T_c$ s extending over a temperature range spanning the two transitions later observed in single crystal and higher-quality polycrystalline specimens. For UPt<sub>3</sub>, however, the temperature difference between the two superconducting transitions does not vary significantly among different samples from  $\sim 60$  mK.

Analysis of the  $C(T)$  data below  $T_{c2} \approx 1.2$  K for sample A and below  $T_{c2} \approx 1.0$  K for sample B revealed that the data could be described well by the expression

$$C_s(T) = \gamma_s(0)T + AT^3, \quad (1)$$

down to  $\sim 0.5$  K, the low-temperature limit of the present experiment. The best fit for sample B is shown in fig. 2 as a solid line below  $\sim 1.0$  K where  $\gamma_s(0) = 42$  mJ/mol K<sup>2</sup> and  $A = 62.9$  mJ/mol K<sup>4</sup>. Assuming eq. (1) holds to  $T = 0$ , the superconducting state entropy  $S_s(T)$  was calculated by integrating  $C_s(T)/T$  given by the fit of eq. (1) to the  $C(T)$  data from 0 to  $T_m \approx 0.5$  K, the lower-temperature limit of the experiment, and the actual  $C_s(T)$  data numerically from  $T_m$  to 1.4 K. The normal-state entropy  $S_n(T)$  was evaluated by integrating  $C_n(T)/T$  from 0 to 1.4 K using  $C_n(T) = \gamma_n(T)T$  and a linear extrapolation of the  $C(T)/T$  data above  $T_{c1} \approx$

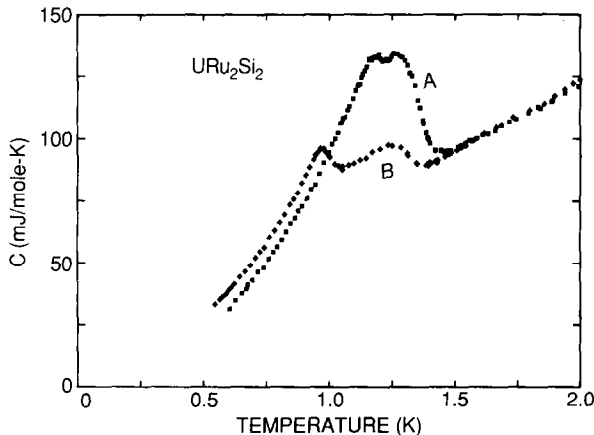


Fig. 1. Specific heat  $C$  vs. temperature  $T$  of two single-crystal specimens of URu<sub>2</sub>Si<sub>2</sub> (denoted A and B) between 0.5 K and 2 K in zero applied magnetic field.

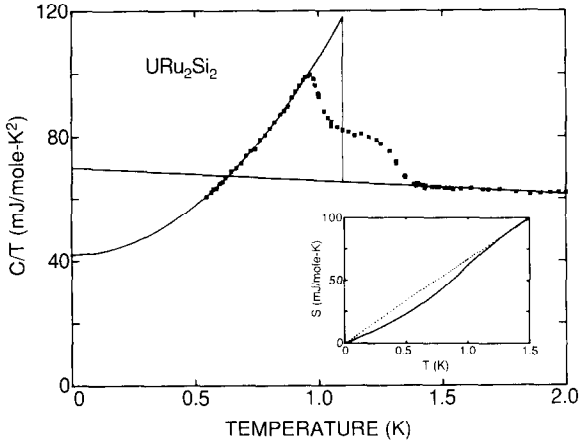


Fig. 2. Specific heat  $C/T$  vs. temperature  $T$  of a single-crystal specimen of URu<sub>2</sub>Si<sub>2</sub> (sample B of fig. 1).  $C(T)/T$  for an ideal single superconducting transition with the same entropy as the data at  $T_{c1}$  is depicted by the solid lines. The solid line through the data below  $T_{c2}$  represents the best fit of  $C_s(T)/T = \gamma_s(0) + AT^2$ . The solid line through the data above  $T_{c1}$  represents the best fit of  $C_n(T)/T = \gamma_n(0) - \alpha T$ . The superconducting- and normal-state entropies  $S_s(T)$  (solid line) and  $S_n(T)$  (dotted line) are shown in the inset.

1.4 K to estimate  $\gamma_n(T)$  below  $T_{c1}$ ; i.e.,

$$\gamma_n(T) = \gamma_n(0) - \alpha T. \quad (2)$$

The best fit of  $\gamma_n(T)$  is shown as a straight line in fig. 2, where  $\gamma_n(0) = 70 \text{ mJ/mol K}^2$  and  $\alpha = 4.3 \text{ mJ/mol K}^3$ .

Shown in the inset of fig. 2 are the resultant  $S_s(T)$  and  $S_n(T)$  curves (represented by solid and dashed lines, respectively) for sample B, where the superconducting-state entropy  $S_s$  above  $T_{c1}$  is equal to the normal-state entropy  $S_n$  within 0.5%. This agreement reflects the accuracy of the fits. Analysis of the  $C(T)$  data for sample A yields the following parameters:  $\gamma_s(0) = 33.4 \text{ mJ/mol K}^2$ ,  $A = 60.3 \text{ mJ/mol K}^4$ ,  $\gamma_n(0) = 75.4 \text{ mJ/mol K}^2$ ,  $\alpha = 7.7 \text{ mJ/mol K}^3$ , and above  $T_{c1}$ ,  $S_s$  is equal to  $S_n$  within 4%.

The finite  $\gamma_s(0)$  and the  $T^3$  temperature dependence which characterize the superconducting-state specific heat of URu<sub>2</sub>Si<sub>2</sub> should provide important clues to the nature of the unconventional superconductivity apparently displayed by this material. The finite  $\gamma_s(0)$  presumably reflects

the existence of a region on the Fermi surface over which the superconducting energy gap vanishes, which may be due to pair breaking by nonmagnetic impurities, while the  $T^3$  temperature dependence may be associated with the distribution of nodes in the anisotropic energy gap over the Fermi surface. The fraction of electronic states involved in the superconductivity  $f_s \equiv [1 - \gamma_s(0)/\gamma_n(0)]$  is  $\sim 56\%$  and  $\sim 40\%$  for samples A and B, respectively. It is noteworthy that previous measurements [27] of  $C(T)$  under pressure on polycrystalline URu<sub>2</sub>Si<sub>2</sub> samples yielded  $C_s(T) = \gamma_s(0)T + BT^2$  below  $T_c$ , with  $\gamma_s(0) = 6.5 \text{ mJ/mol K}^2$ , which is probably an artifact of the distribution of  $T_c$ s in the polycrystalline material. This form does not provide a satisfactory description of the  $C_s(T)$  data for the URu<sub>2</sub>Si<sub>2</sub> single crystal specimens reported here. The behavior of  $C(T)$  below  $T_{c2}$  in URu<sub>2</sub>Si<sub>2</sub> single crystals is also different than in UPT<sub>3</sub> single crystals, where the specific heat in the superconducting state has been found to be of the form  $C_s(T) = \gamma_s(0)T + BT^2$  [22].

Analysis of the specific heat near the critical temperatures  $T_{c1}$  and  $T_{c2}$  using the entropy-conserving construction shown in fig. 2 yields for sample B:  $\Delta C(T_c)/[f_s \gamma_n(T_c) T_c] = 2.0$  where  $T_c$  is the temperature of the ideal single transition specific heat discontinuity.

Specific heat  $C$  versus  $T$  data for sample B, taken between  $\sim 0.5$  and 2.0 K in magnetic fields of 0, 1, 5, 10 and 15 kOe applied parallel to the  $c$ -axis, are displayed in fig. 3 (the 1 kOe data have been omitted for clarity). The two specific-heat jumps diminish, broaden, and shift to lower temperatures with increasing field. Shown in the inset of fig. 3 is the  $H$ - $T$  phase diagram that results from plotting the field dependence of the peaks.

Resistive upper critical field  $H_{c2}$  versus temperature  $T$  data, with  $H \parallel c$  and  $H \parallel a$ , for two URu<sub>2</sub>Si<sub>2</sub> single-crystal specimens cut from sample A are shown in figs. 4 and 5, respectively. The  $H_{c2}(T)$  data were deduced from measurements of the electrical resistivity as a function of temperature in various fixed magnetic fields, where  $T_c$  in each field was defined as the midpoint of the resistive superconducting transition

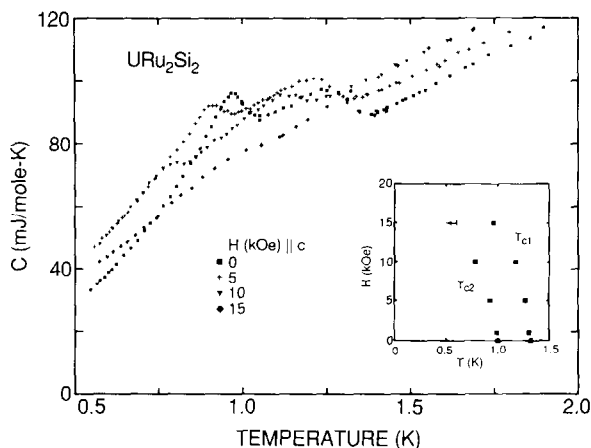


Fig. 3. Specific heat  $C$  vs. temperature  $T$  of a single-crystal specimen of URu<sub>2</sub>Si<sub>2</sub> (sample B) between 0.5 K and 1.6 K in various magnetic fields  $H$  applied parallel to the  $c$ -axis. The dependence of  $T_{c1}$  and  $T_{c2}$  on  $H$  is displayed in the inset.

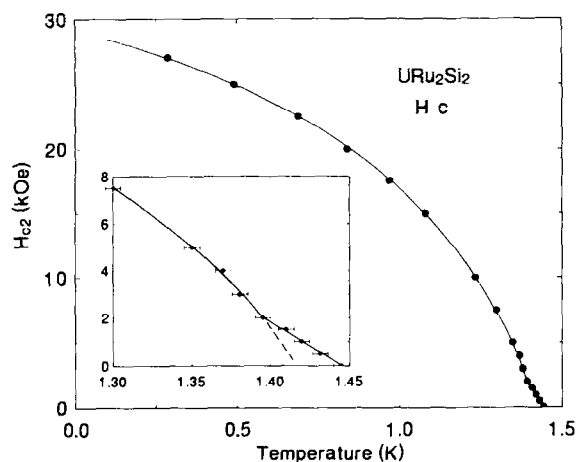


Fig. 4. Upper critical field  $H_{c2}$  vs. temperature  $T$  of a URu<sub>2</sub>Si<sub>2</sub> single-crystal specimen from crystal A, measured resistively with the current  $I$  flowing along the  $a$ -axis and the magnetic field  $H$  applied parallel to the  $c$ -axis. Shown in the inset are  $H_{c2}(T)$  data below 8 kOe which reveal the existence of a kink near 2 kOe. Solid and dashed lines are guides to the eye.

curve. The sample measured with  $H||c$  displayed sharp superconducting transitions with a residual resistivity just above  $T_c$  of  $\rho_0 \approx 26 \mu\Omega \text{ cm}$  and a large zero-field  $T_c \approx 1.45 \text{ K}$ . The sample measured with  $H||a$  exhibited somewhat broader

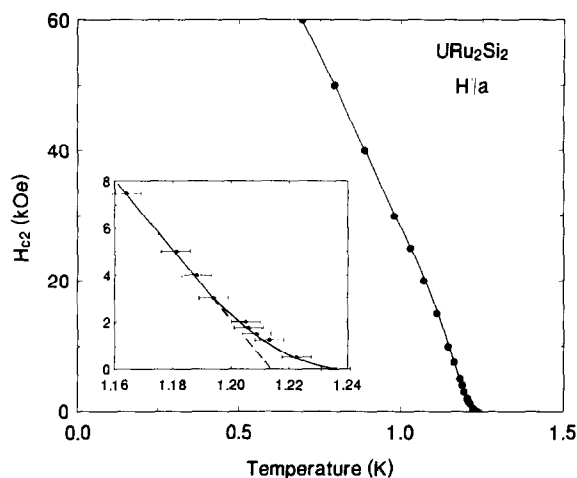


Fig. 5. Upper critical field  $H_{c2}$  vs. temperature  $T$  of a URu<sub>2</sub>Si<sub>2</sub> single crystal specimen from crystal A, measured resistively with the current  $I$  flowing along the  $a$ -axis and the magnetic field  $H$  applied parallel to the  $c$ -axis. Shown in the inset are  $H_{c2}(T)$  data below 8 kOe which reveal the existence of a kink near 2 kOe. Solid and dashed lines are guides to the eye.

superconducting transitions, a residual resistivity  $\rho_0 \approx 17 \mu\Omega \text{ cm}$ , and a smaller  $T_c \approx 1.24 \text{ K}$ . For both specimens, the residual resistivity ratio  $\rho(300 \text{ K})/\rho_0$  is  $\sim 20$ . The difference in quality between the two crystals is probably due to the different locations in the zone-refined rod. The  $H_{c2}(T)$  data in figs. 4 and 5 reveal a large amount of anisotropy with a value  $H_{c2}^a/H_{c2}^c \approx 2.5$  at 0.7 K. The magnitudes, general shapes and anisotropy of the  $H_{c2}(T)$  curves for  $H||c$  and  $H||a$  are similar to those reported previously [28].

Shown in the inset of fig. 4 are the  $H_{c2}(T)$  data for  $H||c$  below 8 kOe which show a distinct kink at  $\sim 2 \text{ kOe}$ . The error bars represent the uncertainty of  $T_c$ . The slope of the curve changes from  $dH_{c2}/dT \approx -40 \text{ kOe/K}$  below 2 kOe to  $\approx -70 \text{ kOe/K}$  for fields above 2 kOe. An extrapolation of the higher field data to zero field, as shown by the dashed line in the inset of fig. 4, yields a critical temperature which is  $\sim 30 \text{ mK}$  below  $T_c$ . It seems unlikely that the kink in the  $H_{c2}(T)$  curve for  $H||c$  is related to a convergence of  $T_{c1}$  and  $T_{c2}$  at  $\sim 2 \text{ kOe}$ , since this would require that  $T_{c2}$  increases rapidly with  $H$  below

3 kOe, in contrast to the parallel shift of  $T_{c1}$  and  $T_{c2}$  to lower temperatures with increasing  $H$  found for sample B from the measurements of  $C(T, H)$  (fig. 3). The inset of fig. 5 reveals a similar deviation from normal behavior below  $\sim 3$  kOe in the  $H_{c2}(T)$  curve for  $H\parallel a$ . In this case, the data display upward curvature below  $\sim 3$  kOe instead of a distinct kink. At zero field, the initial slope is  $dH_{c2}/dT \approx -37$  kOe/K; above 3 kOe,  $H_{c2}$  is linear in  $T$  with a slope of  $-150$  kOe/K. This behavior of the  $H_{c2}(T)$  curve is consistent with the positive curvature observed in previously reported  $H_{c2}(T)$  data taken on single crystal specimens of URu<sub>2</sub>Si<sub>2</sub> for  $H\parallel c$  and  $H\parallel a$ , where the density of data was not sufficiently high to establish the possible existence of a kink for  $H\parallel c$  [28]. The positive curvature of  $H_{c2}(T)$  in low fields for URu<sub>2</sub>Si<sub>2</sub> has been explained in terms of the effect of coupled antiferromagnetic and multicomponent superconducting order parameters [29]. A similar situation was encountered for the heavy-electron superconductor UPt<sub>3</sub>; whereas the original measurements of  $H_{c2}(T)$  on single-crystal specimens for  $H\parallel c$  and  $H\perp c$  revealed a strong positive curvature near  $T_c$  [9], subsequent measurements established the existence of a kink in  $H_{c2}(T)$  for  $H\perp c$  [30, 31]. For both URu<sub>2</sub>Si<sub>2</sub> and UPt<sub>3</sub>, the kink in  $H_{c2}(T)$  is observed for  $H$  in the direction of the antiferromagnetically aligned moments.

The double superconducting transitions revealed by the  $C(T, H)$  measurements and the positive curvature (along with the possible kink for  $H\parallel c$ ) in the  $H_{c2}(T)$  data taken on the single-crystal specimens of URu<sub>2</sub>Si<sub>2</sub> reported herein may be associated with coupled antiferromagnetic and multicomponent superconducting-order parameters. However, it is difficult to rule out the possibility that the two superconducting phases observed in single-crystal specimens A and B are associated with two regions of the single crystal which are characterized by different compositions, states of strain, atomic order, etc. However, this seems unlikely on the basis of the sharpness of the superconducting transitions observed in the specific heat and the structural and chemical analysis we have performed on specimen B. More extensive experiments on

these and other single-crystal URu<sub>2</sub>Si<sub>2</sub> specimens are in progress in order to determine whether or not the multiple superconducting phases are intrinsic, and, if so, to test relevant theories of superconductivity in heavy-electron compounds.

#### Note added in proof

Subsequent to submitting this manuscript, we performed resistive upper critical field measurements on a rod cut from crystal B, with the field applied parallel to the  $c$ -axis. The results reveal a kink, similar to that for crystal A (see fig. 4), occurring at a field of 2 kOe. This specimen also displayed many unusual features including a superconducting transition with an unprecedentedly high onset temperature of 2 K,  $T_c(50\%) = 1.64$  K,  $\Delta T_c(10-90\%) = 0.38$  K, a residual resistivity ratio RRR of 60, and a residual resistivity  $\rho_0 \approx 6 \mu\Omega$  cm. We remark that an anomaly has been seen in the specific heat of a polycrystalline sample of URu<sub>2</sub>Si<sub>2</sub> at  $\sim 2.7$  K [32], which the authors suggest could be due to rearrangement of the spin density wave. Very recently, we received a preprint [33] of a similar specific-heat study on single crystals of URu<sub>2</sub>Si<sub>2</sub> in which the authors claim that the double transitions they observe are due to different unique crystal phases which are as yet unidentified.

#### Acknowledgements

We thank G. Nieva for assistance in data analysis and S.H. Han for assistance in preparing the figures. Research at UCSD was supported by the US Department of Energy under Grant No. DE-FG03-86ER45230 and the National Science Foundation under Grant No. DMR-87-21455. Work at Los Alamos was performed under the auspices of the US Department of Energy.

#### References

- [1] F. Steglich, J. Aarts, C.D. Bredl, W. Lieke, D. Meschede, W. Franz and H. Schafer, Phys. Rev. Lett. 43 (1979) 1892.

- [2] H.R. Ott, H. Rudigier, Z. Fisk and J.L. Smith, *Phys. Rev. Lett.* 50 (1983) 1595.
- [3] G.R. Stewart, Z. Fisk, J.O. Willis and J.L. Smith, *Phys. Rev. Lett.* 52 (1984) 679.
- [4] T.T.M. Palstra, A.A. Menovsky, J. van den Berg, A.J. Dirkmaat, P.H. Kes, G.J. Nieuwenhuys and J.A. Mydosh, *Phys. Rev. Lett.* 55 (1985) 2727.
- [5] M.B. Maple, J.W. Chen, Y. Dalichaouch, T. Kohara, C. Rossel, M.S. Torikachvili, M.W. McElfresh and J.D. Thompson, *Phys. Rev. Lett.* 56 (1986) 185.
- [6] W. Schlabitz, J. Baumann, B. Pollit, U. Rauchswalbe, H.M. Mayer, U. Ahlheim and C.D. Bredl, *Z. Phys.* B 62 (1986) 171.
- [7] Z. Fisk, D.W. Hess, C.J. Pethick, D. Pines, J.L. Smith, J.D. Thompson and J.O. Willis, *Science* 239 (1988) 33.
- [8] M.B. Maple, J.W. Chen, S.E. Lambert, Z. Fisk, J.L. Smith, H.R. Ott, J.S. Brooks and M.J. Naughton, *Phys. Rev. Lett.* 54 (1985) 477.
- [9] J.W. Chen, S.E. Lambert, M.B. Maple, Z. Fisk, J.L. Smith, G.R. Stewart and J.O. Willis, *Phys. Rev. B* 30 (1984) 1583 (Rapid Commun.).
- [10] R.N. Kleiman, D.J. Bishop, H.R. Ott, Z. Fisk and J.L. Smith, *Phys. Rev. Lett.* 64 (1990) 1975.
- [11] G. Aeppli, E. Bucher, C. Broholm, J.K. Kjems, J. Baumann and J. Hufnagl, *Phys. Rev. Lett.* 60 (1988) 615.
- [12] C. Broholm, J.K. Kjems, W.J.L. Buyers, P. Mathews, T.T.M. Palstra, A.A. Menovsky and J.A. Mydosh, *Phys. Rev. Lett.* 58 (1987) 1467.
- [13] G. Aeppli, A. Goldman, G. Shirane, E. Bucher and M.-Ch. Lux-Steiner, *Phys. Rev. Lett.* 58 (1987) 808.
- [14] D.W. Cooke, R.H. Heffner, R.L. Hutson, M.E. Shillaci, J.L. Smith, J.O. Willis, D.E. McLaughlin, C. Boekema, R.L. Lichti, A.B. Denison and J. Oostens, *Hyperfine Interactions* 31 (1986) 425.
- [15] A. de Visser, J.C.P. Klaasse, M. van Sprang, J.J.M. Franse, A. Menovsky and T.T.M. Palstra, *J. Magn. & Magn. Mater.* 54–57 (1986) 375.
- [16] A.P. Ramirez, B. Batlogg, E. Bucher and A.S. Cooper, *Phys. Rev. Lett.* 57 (1986) 1072.
- [17] G.R. Stewart, A.L. Giorgi, J.O. Willis and J. O'Rourke, *Phys. Rev. B* 34 (1986) 4629.
- [18] H. Amitsuka, T. Sakakibara, Y. Miyako, K. Sugiyama, A. Yamagishi and M. Date, to appear in the Proc. of the Yamada Conf. XXV on Magnetic Phase Transition, Osaka, Japan (April 13–16, 1990).
- [19] Y. Dalichaouch, M.B. Maple, M.S. Torikachvili and A.L. Giorgi, *Phys. Rev. B* 39 (1989) 2423.
- [20] H.R. Ott, H. Rudigier, Z. Fisk and J.L. Smith, *Phys. Rev. B* 31 (1985) 1651.
- [21] S.E. Lambert, Y. Dalichaouch, M.B. Maple, J.L. Smith and Z. Fisk, *Phys. Rev. Lett.* 57 (1986) 1619.
- [22] R.A. Fisher, S. Kim, B.F. Woodfield, N.E. Phillips, L. Taillefer, K. Hasselbach, J. Flouquet, A.L. Giorgi and J.L. Smith, *Phys. Rev. Lett.* 62 (1989) 1411.
- [23] K. Hasselbach, L. Taillefer and J. Flouquet, *Phys. Rev. Lett.* 63 (1989) 93.
- [24] R.N. Kleiman, P.L. Gammel, E. Bucher and D.J. Bishop, *Phys. Rev. Lett.* 62 (1989) 328.
- [25] E.I. Blount, C.M. Varma and G. Aeppli, *Phys. Rev. Lett.* 64 (1990) 3074.
- [26] R. Joynt, *J. Phys.: Condens. Matter* 2 (1990) 3415.
- [27] R.A. Fisher, S. Kim, Y. Wu, N.E. Phillips, M.W. McElfresh, M.S. Torikachvili and M.B. Maple, *Physica B* 163 (1990) 419.
- [28] L.E. DeLong, D. Togliatti, G.W. Lehman, W.-K. Kwok, G.W. Crabtree, K.G. Vandervoort and D.G. Hinks, *Physica B* 163 (1990) 499.
- [29] W.K. Kwok, L.E. DeLong, G.W. Crabtree, D.G. Hinks and R. Joynt, *Phys. Rev. B* 41 (1990) 11649.
- [30] L. Taillefer, F. Piquemal and J. Flouquet, *Physica C* 153–155 (1988) 451.
- [31] U. Rauchschwalbe, U. Allheim, F. Steglich, D. Rainer and J.J.M. Franse, *Z. Phys.* B 60 (1985) 379.
- [32] M.A. López de la Torre, S. Vieira, R. Villar, M.B. Maple and M.S. Torikachvili, Proc. of the 19th Int. Conf. on Low Temperature Physics, Brighton, England (August 1990), *Physica B* 165 & 166 (1990) 385.
- [33] A.P. Ramirez, T. Siegrist, T.T.M. Palstra, J.D. Garrett, E. Brück, A.A. Menovsky and J.A. Mydosh, preprint.