Multiband superconductivity in Ta$_4$Pd$_3$Te$_{16}$ with anisotropic gap structure

Wen-He Jiao$^1$, Yi Liu$^{2,5}$, Yu-Ke Li$^3$, Xiao-Feng Xu$^3$, Jin-Ke Bao$^{2,5}$, Chun-Mu Feng$^2$, S Y Li$^{4,5}$, Zhu-An Xu$^{2,5}$ and Guang-Han Cao$^{2,5}$

1 Department of Physics, Zhejiang University of Science and Technology, Hangzhou 310023, People’s Republic of China
2 Department of Physics, Zhejiang University, Hangzhou 310027, People’s Republic of China
3 Department of Physics, Hangzhou Normal University, Hangzhou 310036, People’s Republic of China
4 State Key Laboratory of Surface Physics, Department of Physics and Laboratory of Advanced Materials, Fudan University, Shanghai 200433, People’s Republic of China
5 Collaborative Innovation Centre of Advanced Microstructures, Nanjing 210093, People’s Republic of China

E-mail: whjiao@zust.edu.cn and ghcao@zju.edu.cn

Received 20 March 2015, revised 18 June 2015
Accepted for publication 24 June 2015
Published 27 July 2015

Abstract

We carried out measurements of the magnetoresistance, magnetic susceptibility and specific heat on crystals of the low-dimensional transition metal telluride Ta$_4$Pd$_3$Te$_{16}$. Our results indicate that Ta$_4$Pd$_3$Te$_{16}$ is an anisotropic type-II superconductor in the clean limit with the extracted Ginzburg–Landau parameter $\kappa_{GL} = 84$. The upper critical field $H_{c2}(T)$ shows an anomalous temperature dependence at low temperatures and the anisotropy of $H_{c2}(T)$ is strongly $T$-dependent, both of which indicate a multiband scenario. The electronic specific heat $C_{el}(T)$ can be consistently described by a two-gap ($s + d$ waves) model from the base temperature $T/\theta_{D} \sim 0.12$ up to $T_c$. Our results suggest nodal and multiband superconductivity in Ta$_4$Pd$_3$Te$_{16}$.

Keywords: quasi-one-dimensional (Q1D) characteristics, multiband superconductivity, gap structure

(Some figures may appear in colour only in the online journal)

1. Introduction

Exploring exotic pairing mechanisms in new superconducting compounds has always been one of the most attractive issues in condensed matter physics. Although the Bardeen–Cooper–Schrieffer (BCS) theory [1] provides excellent explanations for the conventional phonon-mediated $s$-wave superconductor, the successive emergence of unconventional superconductivity, claimed to be in either the singlet $\pm s$-wave [2] and $d$-wave pairing states [3, 4], or the triplet $p$-wave [5, 6] and $f$-wave pairing states [7], presents great challenges for physicists to uncover the variously exotic non-phonon-mediated pairing mechanisms. Spin or charge fluctuations, which always appear in low-dimensional structures, were often regarded as the pairing glues for a large number of unconventional superconductors, such as the cuprates [8], iron-based superconductors [2], quasi-one-dimensional (Q1D) superconductors [9, 10], and heavy-fermion superconductors [11, 12]. Among them, multiband superconductivity and symmetry-imposed nodes were commonly observed as evidenced by a variety of techniques, including thermodynamic approaches [13–15]. In this regard, the gained information on gap symmetry has significant meanings in understanding the novel pairing mechanisms.

Recently, we discovered bulk superconductivity with $T_c = 4.6$ K in the transition metal telluride Ta$_4$Pd$_3$Te$_{16}$ [16]. This material has a layered structure with Q1D characteristics consisting of PdTe$_2$ chains, TaTe$_3$ chains and Ta$_2$Te$_4$ double chains along the crystallographic $b$-axis. The $(1 0 3)$ planes are formed by the connection of the chains mentioned above along the $[3 0 1]$ direction. The projection view of the layered structure is illustrated in the inset of figure 1(c). More details about the crystal structure can be seen in [16]. These structural
features are well reflected in the morphology of the crystals as shown in the inset of figure 1(a). For simplicity, hereafter we define the $a^*$-axis as parallel to the [3 0 1] direction and the $c^*$-axis as perpendicular to the $(\overline{1} 0 3)$ plane. Compared with layered chalcogenide superconductors $\text{Nb}_3\text{Pd}_x\text{Se}_7$ [17] and $\text{M}_2\text{Pd}_x\text{Q}_5$ ($\text{M} = \text{Nb}$ and $\text{Ta}$, $\text{Q} = \text{S}$ and $\text{Se}$) [18–22] with similar Q1D structures, $\text{Ta}_4\text{Pd}_3\text{Te}_{16}$ is a stoichiometric compound with flat two-dimensional sheets and it shows stronger electron–electron interactions [16]. Thermal conductivity measurements demonstrate the presence of nodes in the superconducting gap by the evidence of a large residual $\rho(0)$ in the zero field and the rapid increase of $\rho(T)$ in the magnetic field, mimicking the behaviour of $d$-wave cuprate superconductor $\text{Tl}_2\text{Ba}_2\text{CuO}_6$ [23]. Furthermore, a temperature–pressure superconducting dome was observed, leading to the expectation that certain density-wave orders may neighbour the superconducting dome. According to the result of electronic-structure calculations made by Singh [24], any nearby density wave instability, if exists, would be a charge-density wave (CDW) but not a spin-density wave (SDW) as the transition metal’s contribution to the density of states is rather small. The feature of a CDW-like ordering is indeed observed in scanning tunneling microscopy (STM) measurements [25]. Besides, an $s$-wave pairing state from phonons associated with the Te–Te $p$ bonding and a Fermi surface associated with Te $p$ bands are argued to be the most possible case. To explain the results on the thermal conductivity, the author also proposes the likelihood of $\text{Ta}_4\text{Pd}_3\text{Te}_{16}$ being a clean multi-gap superconductor where the gap ratio is significantly large [24]. However, more recently, low-temperature STM measurements show evidence for the presence of an anisotropic superconducting gap with gap minima or even nodes [26]. Thus, the issue of gap symmetry in $\text{Ta}_4\text{Pd}_3\text{Te}_{16}$ is worth addressing further.

In the current work, we investigate the superconducting properties of $\text{Ta}_4\text{Pd}_3\text{Te}_{16}$ crystals via systematic magnetoresistivity (MR), magnetic susceptibility and specific heat measurements. The results indicate that $\text{Ta}_4\text{Pd}_3\text{Te}_{16}$ is an anisotropic type-II superconductor in the clean limit. The upper critical fields $H_{c2}(T)$ were estimated to be 4.2, 9.6 and 3.3 T for fields applied along the three axes, $a^*$, $b$ and $c^*$, respectively. We observed the strong $T$-dependent anisotropy of $H_{c2}(T)$ and the linear increase of $H_{c2}$, both of which suggest multiband superconductivity. The zero-field heat capacity data can be best described by a two-gap model with an anisotropic gap

![Figure 1. Magnetoresistivity of the $\text{Ta}_4\text{Pd}_3\text{Te}_{16}$ crystal for (a) $H \parallel a^*$, (b) $H \parallel b$ and (c) $H \parallel c^*$. (d) The extracted superconducting upper critical field $H_{c2}(T)$ for different field orientations. Werthamer–Helfand–Hohenberg (WHH) fitting is made to the data for $H \parallel b$, represented by the red dashed lines. The black dashed lines show linear fittings. The inset of (a) shows an image of the crystal under an optical microscope, from which the crystallographic directions can be easily identified. The crystal structure of $\text{Ta}_4\text{Pd}_3\text{Te}_{16}$ viewed perpendicular to the $(\overline{1} 0 3)$ plane is plotted in the inset of (c). The inset of (d) shows the anisotropy of $H_{c2}(T)$.](image)
structure. In addition, the electronic specific-heat coefficient in the mixed state, \( \gamma_{\text{EL}}(H) \), exhibits a nonlinear behavior. Thus, our results suggest two energy gaps with an anisotropic gap structure are associated with the superconductivity in Ta\(_4\)Pd\(_3\)Te\(_{16}\).

2. Experimental details

Single crystals of Ta\(_4\)Pd\(_3\)Te\(_{16}\) were grown by a self-flux technique as previously described [16]. By applying both x-ray diffraction and energy-dispersive x-ray spectroscopy, we determine the chemical composition of the crystals used in this work for the measurements is Ta\(_4\)Pd\(_3\)Te\(_{16}\) with no detectable impurities. Moreover, a large residual resistivity ratio (\( \sim 26 \)), sharp superconducting transition (\( \Delta T_c = 1.1 \) K) and large shielding volume fraction (87% at 1.9 K) further corroborate the high quality of the as-grown crystals. To ensure the data obtained are more reliable, we elaborately selected crystals among the as-grown crystals for the measurements, all of which have shiny surfaces. MR measurements were carried out by a stand four-probe technique with current \( I = 2 \) mA applied along the \( b \)-axis. The specific heat for a collection of five needle-like crystals with a total mass of \( m = 4.68(2) \) mg was measured by a long relaxation method utilizing a commercial \(^3\)He microcalorimeter (Quantum Design PPMS-9). In various magnetic fields, the thermometer on the calorimeter puck was calibrated before the measurements, and the addenda were predetermined in a separate run. Magnetic susceptibility measurement was performed using a superconducting quantum interference device magnetometer (MPMS-5).

3. Results and discussion

Figure 1 encapsulates the \( b \)-axis MR (\( \rho_B \)) and the extracted \( H_{c2}^b \) with fields applied along \( a^* \), \( b \) and \( c^* \), respectively. To eliminate ambiguity from the superconducting fluctuations, the 50% criterion was used in determining \( H_{c2}^b \), i.e. the field at which \( \rho_B \) reaches 50% of the normal-state resistivity. We employed the Werthamer–Helfand–Hohenberg (WHH) formula for an isotropic one-band BCS superconductor in a dirty limit to fit \( H_{c2}^b(T) \) [27]. Apparently, at low temperatures, the one-band WHH model fails to satisfy the extracted \( H_{c2}^b(T) \). By linear extrapolations, \( H_{c2}^b(T) \) and \( H_{c2}^c(T) \) are estimated to be 4.2, 9.6 and 3.3 T, respectively. The estimated value of \( H_{c}^b(T) \) is close to the Pauli–Clogston limiting field \( H_p = 1.84T_c \approx 8.5 \) T. Besides, all of the three curves show an almost linear \( T \)-dependence at low temperatures, which is consistent with a previous report [23] but in sharp contrast with what it should display in most superconductors [27, 28], i.e. a concave down curvature at low temperatures. This anomalous behaviour was regarded as the evidence for multiband superconductivity in iron-based superconductors [29, 30], resulting from the gap opening in multi-Fermi-surface sheets at different temperatures. Since the gap magnitude determines the \( H_{c2} \) value, the multi-gap scenario makes suppositions of \( H_{c2} \) at low temperatures, which could lead to the anomalous low-temperature upper critical field [18]. Moreover, as shown in the inset of figure 1(d), the strong \( T \)-dependent superconducting anisotropy \( \gamma = H_{c2}^b/H_{c2}^c \) or \( H_{c2}^b/H_{c2}^a \) provides further evidence of a multiband scenario as the case in two-band superconductor MgB\(_2\) and most iron-based superconductors [31, 32]. Using the anisotropic GL formula

\[
H_{c2}^b(0) = \phi_0/2\pi\xi_b(0)\xi_b(0),
\]

where \( \phi_0 \) is the flux quantum and \( \xi_b(0) \) is the GL coherence length along the \( b \)-direction; \( \xi_b(0) \) at zero temperature is calculated to be 66.1, 151.0 and 51.9 \( \AA \) for \( a^* \), \( b \) and \( c^* \), respectively. Obviously, the interchain coherence lengths \( \xi_b^a(0) \) and \( \xi_b^c(0) \) are much longer than the distance between any two adjacent chains in Ta\(_4\)Pd\(_3\)Te\(_{16}\), denoting a continuous superconducting phase across the chains. In other words, the superconductivity here is anisotropic but three-dimensional in nature, similar to that of recently discovered Q1D superconductors Nb\(_2\)Pd\(_3\)Se\(_5\) and Ta\(_4\)Pd\(_3\)Se\(_5\) [19, 20]. For the normal state, the longitudinal MR (\( H || J \)) response is negligibly small, while the in-chain MR (\( H \perp J \)) is obviously large in magnitude and positive, which is typical of a Q1D metal due to the change in carrier trajectories induced by the Lorentz force [33]. In addition, the electronic mean free path (\( l_B \)) could be roughly estimated to be 0.7 \( \mu m \), by using the Drude model with the below Sommerfeld coefficient and the residual resistivity \( \rho_\text{0}(2.34 \times 10^{-8} \text{ } \Omega \cdot \text{m}) \) [16, 20, 34]. This estimation implies that Ta\(_4\)Pd\(_3\)Te\(_{16}\) is a superconductor in the clean limit (\( l_B > \xi_b \)). The slightly large mean free path is consistent with the result of energy-dispersive x-ray spectroscopy [16], which indicates no significant deficiency for Pd in Ta\(_4\)Pd\(_3\)Te\(_{16}\), in sharp contrast with the \( M_T \text{Pd}_xQ_y(M = \text{Nb and Ta}, \text{ } Q = \text{S and Se}) \) system.

The lower critical field values, \( H_{c2}^b(T) \), were determined from low-field magnetization curves \( M(H) \) with the field applied along the \( b \)-axis as shown in figure 2. The low-field parts almost overlap with the Meissner line (the solid red line in figure 2(a)) due to the Meissner effect. Thus, \( H_{c2}^b(T) \) could be defined at the point where \( M(H) \) deviates by 2% from the perfect Meissner response, and the extracted results are plotted in figure 2(b). Since our crystal is needle-like and the demagnetization factor for the field along the needle-like direction is negligibly small, \( H_{c2}^b(0) \) can be directly estimated to be 29.9 Oe by fitting the extracted data to the formula \( H_{c2}(T) = H_{c2}(0)[1 - (T/T_c)^2] \), represented by the dashed red line in figure 2(b). With the results for \( H_{c2}^b(0) \) and \( H_{c2}^c(0) \), we calculated the GL parameter \( \kappa_{\text{GL}} \) to be about 84 using the equation \( H_{c2}(0)/H_{c2}(T) = 2\xi_b^a/\kappa_{\text{GL}} \). The above results indicate that Ta\(_4\)Pd\(_3\)Te\(_{16}\) is an extremely type-II superconductor.

Figure 3 presents the \( T \)-dependent specific heat of the Ta\(_4\)Pd\(_3\)Te\(_{16}\) crystals divided by the temperature at zero magnetic field. A sharp anomaly, denoting the superconducting transition, can be clearly observed at \( T_c \sim 4.14 \) K (defined by an entropy-conserving construction). In figure 3(a), the raw heat capacity data between 4.5 K and 7 K is fitted to the formula \( C/T = \gamma + \beta T^2 \), and the fitting gives parameters \( \gamma = 51.2(1) \text{ } \text{mJ} \text{mol}^{-1} \text{K}^2 \) and \( \beta = 13.53(1) \text{ } \text{mJ} \text{mol}^{-1} \text{K}^2 \), both
of which are slightly larger than those in our previous report [16]. This small discrepancy is possibly due to the measurement precision as well as the uncertainty of the sample mass weighed. Besides, a small residual linear term $\gamma_0 = 5.1 \text{ mJ mol}^{-1} \text{ K}^2$ ($\sim 10\%$) exists, as observed from the intercept of $C/T$ versus $T^2$ in the $T \to 0$ limit. Generally, this linear term
could be attributed to the presence of nodal quasiparticles for
a nodal superconducting gap or a small fraction of nonsuper-
conducting metallic impurity phase. However, if we assume
the impurity phase has the same Sommerfeld coefficient, an ∼
10% impurity phase should be easily detected by x-ray diffraction,
which is inconsistent with our results. Therefore, we con-
clude the explanation of the presence of nodal quasiparticles
for a nodal superconducting gap is more likely in this case, and
this conclusion is consistent with our fitting results as shown
below. By subtracting the phononic contribution, the elec-
tronic specific heat can be obtained by: 

\[ C_s(T) = C(T) - \beta T^3 \]

which is plotted in figure 3(b) as \( C_s/T \) versus \( T/T_c \). The zero-
field data at low temperature is obviously irreconcilable with
the conventional \( s \)-wave order parameter as the significant
quasiparticle excitations.

The so-called \( \alpha \) model, which was devised to simulate
the strong-coupling effect, has gained significant success in
explaining the properties of strong-coupling superconductor-
s [35]. Within this model, the temperature dependence of the energy gap \( \Delta(T) \) approximately follows weak-coupling
BCS behaviour multiplied by a dimensionless parameter \( \alpha \).
In the BCS theory, the entropy \( S \) in the superconducting state
is given by [36]

\[ S = -\frac{3\gamma_n}{k_B T} \int_0^{2\pi} \int_0^\infty f \ln(1-f) \ln(1+f) d\phi d\gamma \]  

where \( f \) is the Fermi function \( f = (1 + e^{E/h\omega T})^{-1} \) with the qua-
siparticle energy \( E = \sqrt{\Delta^2(T, \phi) + \Delta^2} \), \( \gamma_n \) is the normal state \( \gamma \)
of the superconducting part, and \( \Delta(T, \phi) \) is the temperature
and angle dependence of the gap function. The electronic
heat capacity is thus calculated by \( C_e = T \partial S/\partial T \). To eluci-
date the superconducting order parameter, the raw data of \( C_e \)
is analyzed and fitted by various models, i.e. the isotropic \( s \)-
wave function, anisotropic \( d \)-wave function, two-fold-sym-
metric anisotropic \( s \)-wave function \( \Delta(\phi) = a_1 + a_2 \cos 2\phi \),
and two-gap scenarios \( s + d \) waves and \( s + d \) waves. The
data fitted by the above models is from the base temperature
\( T/T_c \sim 0.12 \) up to \( T_c \), the fitting range of which is large enough
to draw reasonable conclusions [15]. The contribution of \( C_e \)
from nodal quasiparticles or the small fraction of nonsuper-
conducting metallic impurity phase is regarded as \( \gamma_n T \) in our
fittings. The fitting curves for the cases of single-band \( s \)-
wave and two-band \( s + d \) waves are plotted in figure 3(b),
from which one can unambiguously observe that the two-
gap \( s + d \) waves) model best captures the experimental
data in the fitting range. The fitting gives the following
parameters: \( \alpha^s = 0.916 \) (for \( s \) wave), \( \alpha^d = 1.652 \) (for \( d \) wave)
and the ratio of weight \( \gamma_n^s : \gamma_n^d = 33.5 : 66.5 \), where the par-
tial Sommerfeld coefficient \( \gamma_n^{s(d)} \) characterizes each band. The
nodal quasiparticles for the nodal superconducting gap or
impure phase are expected to be the source of the finite value
\( \gamma_n \) in the \( T \to 0 \) limit for this case. The fittings with other gap
functions (full-gap cases) mentioned above deviate from
the experimental data significantly, especially in the low-
temperature region, a close-up view of which is displayed
in figure 3(c). For the full-gap cases, the residual linear term
\( \gamma_n \) should come from a small amount of nonsuperconducting
metallic impure phase. In order to show more clearly the
deviations of the fitting curves from the data for the case of
the \( s + d \) waves, \( s + s \) waves and anisotropic \( s \)-wave, we plot the differences in figure 3(d). Therefore, our result
strongly suggests Ta4Pd3Te16 is a two-gap superconductor
with the pairing symmetry of \( s + d \) waves. This fitting is
consistent with the STS study as the temperature depen-
dence of tunneling spectra can be well fitted with \( s + d \)
waves (the anisotropic \( s \)-wave symmetry can describe their
data as well while in our heat-capacity study it cannot) [26].
In addition, by calculating the maximum gap value using the
derived parameters \( \Delta_{\text{max}} = 0.335 \ast \Delta^s + 0.665 \ast \Delta^d \), we find
that \( \Delta_{\text{max}}/k_B T_c \approx 2.47 \), very close to the value 2.3 reported in
[26]. The scenario of two-band \( s \)-wave gaps with a signifi-
cant ratio has been proposed to be possible in understanding
data on thermal conductivity [24]. However, our analysis of
the heat capacity does not provide sufficient evidence for this
possibility. On the contrary, the evidence of an anisotropic

\[ \Delta^s(\phi) = a_1 + a_2 \cos 2\phi \]

Figure 4. (a) Specific heat of Ta4Pd3Te16 crystals in selected magnetic fields parallel to \( c^* \)-axis, plotted as \( C/T \) versus \( T^2 \). (b) The plots of \( C/T \) versus \( T^2 \) in the low-\( T \) region. For each applied field, \( \gamma(H) \equiv \lim_{T \to 0} C(T,H)/T \) was determined from a linear extrapolation of
the experimental data in the temperature range 0.5–1.3 K. The inset of (b) shows the magnetic field dependence of the electronic specific-heat
coefficient \( \gamma(H) \) in the mixed state.
multi-gap structure is consistent with the study of thermal conductivity [23], which suggests the presence of nodes in the superconducting gap. Overall, our result reported here reconciles with the previous experimental studies regarding the pairing symmetry in Ta₄Pd₃Te₁₆.

As the magnetic field dependence of specific heat at low temperatures is instructive for quasiparticle excitations, we measured the low-T specific heat of Ta₄Pd₃Te₁₆ crystals under magnetic fields (μ₀H ≲ 1.4 T) for H || c° as shown in figure 4(a). The heat capacity anomaly is gradually suppressed to lower temperatures with the increase of field. The enlarged part of the data is displayed in figure 4(b), from which one can observe that minor upturns under μ₀H = 0.3 and 0.5 T appear at low temperatures, probably stemming from the Schottky anomaly. Therefore, we extracted the field-dependent electronic coefficient γ(H) by a linear extrapolation of γ(H) ≡ limT→0 δC(T, H)/T, without considering the upturns under 0.3 and 0.5 T. The fitting range was set to be between 0 K and ~1.3 K. The obtained results are presented in the inset of figure 4(b) as γ(0, H) versus H. In fully gapped conventional type-II superconductors, it is generally known that γ(H) should be linearly proportional to the number of field-induced vortices [37], i.e. γ(H) H. However, we find in Ta₄Pd₃Te₁₆, a power-law fitting provides the relation γ(H) H0.48, thereby ruling out isotropic s-wave pairing symmetry. In the case of two isotropic s-wave superconducting gaps, γ(H) is featured by an intersection of two s-waves, e.g. MgB₂ [38], NbSe₂ [39], and SrPt₂As₂ [40]. The nonlinear behavior observed here is seemingly in contrast with the above scenario. Although H behaviour was once considered as evidence of d-wave superconductors due to the Doppler shift of the extended quasiparticle excitation spectrum [41], this kind of nonlinear behavior was also frequently observed in many multiband superconductors, such as TiN₃Se₂ [15]. Overall, the nonlinear behavior for γ(H) could be regarded as an evidence of multiband superconductivity.

4. Concluding remarks

In summary, we have investigated the superconducting properties of Ta₄Pd₃Te₁₆ crystals. Our measurements indicate Ta₄Pd₃Te₁₆ is a new anisotropic type-II superconductor in the clean limit with the extracted Ginzburg–Landau parameter κGL = 84. The anomalous T-dependent Hc₂ at low temperatures and the strong T-dependent anisotropy of Hc₂ suggest multiband superconductivity. Indeed, the zero-field electronic heat capacity data, Cₑ, can be satisfactorily described in terms of a two-gap (s + d waves) model. The electronic heat capacity coefficient, γ(H), exhibited a nonlinear behavior. Thus, Ta₄Pd₃Te₁₆ appears to be a rare example of a two-gap superconductor with the gap symmetry of s + d waves rather than a multiple fully gapped s-wave symmetry. This superconducting state is very interesting and worthy of further investigation.

Acknowledgments

We would like to thank H Yuan and Y Luo for their helpful discussions. This work is supported by the Zhejiang Provincial Natural Science Foundation of China (No. LQ15A040005), the National Basic Research Program of China (No. 2011CBA00103) and the National Science Foundation of China (Nos. 11190023 and 11474252).

References

[1] Bardeen J, Cooper L N and Schrieffer J R 1957 Phys. Rev. 108 1175
[2] Hirschfeld P J, Korshunov M M and Mazin I I 2011 Rep. Prog. Phys. 74 124508
[3] Tsuei C C and Kirtley J R 2000 Rev. Mod. Phys. 72 969
[4] An K, Sakakibara T, Settai R, Onuki Y, Hiragi M, Ichikoh M and Machida K 2010 Phys. Rev. Lett. 104 037002
[5] Mackenzie A P and Maeno Y 2000 Rev. Mod. Phys. 75 657
[6] Xu X F et al 2009 Phys. Rev. Lett. 102 206602
[7] Mazin I and Johannes M D 2005 Nat. Phys. 1 91
[8] Lee P A, Nagaosa N and Wen X G 2006 Rev. Mod. Phys. 78 18
[9] Tanaka Y, Yanase Y and Ogata M 2004 J. Phys. Soc. Japan 73 2053
[10] Kuroki K and Tanaka Y 2005 J. Phys. Soc. Japan 74 1694
[11] Mathur N D, Grosche F M, Julian S R, Walker I R, Freye D M, Haselwimmer R K W and Lonzarich G G 1998 Nature 394 39
[12] Jourdan M, Huth M and Adrian H 1999 Nature 398 47
[13] Mu G, Luo H Q, Wang Z S, Shan L, Ren C and Wen H H 2009 Phys. Rev. B 79 174501
[14] Hu J, Liu T J, Qian B, Rotaru A, Spinu L and Mao Z Q 2011 Phys. Rev. B 83 134521
[15] Wang H D, Dong C H, Mao Q H, Khan R, Zhou X, Li C X, Chen B, Yang J H, Su Q P and Fang M H 2013 Phys. Rev. Lett. 111 207001
[16] Jiao W H, Tang Z T, Sun Y L, Liu Y, Tao Q, Feng C M, Zeng Y W, Xu Z A and Cao G H 2014 J. Am. Chem. Soc. 136 1284
[17] Zhang Q R, Rhodes D, Zeng B, Besara T, Siegrist T, Johannes M D and Balicas L 2013 Phys. Rev. B 88 024508
[18] Zhang Q, Li G, Rhodes D, Kiswandhi A, Besara T, Zeng B, Sun J, Siegrist T, Johannes M D and Balicas L 2013 Sci. Rep. 3 1446
[19] Khim S et al 2013 New J. Phys. 15 123031
[20] Lu Y F, Takayama T, Bangura A F, Katsura Y, Hashizume D and Takagi H 2014 J. Phys. Soc. Japan 83 023702
[21] Zhou N et al 2014 Phys. Rev. B 90 094520
[22] Jha R, Tiwari B, Rani P, Ishikawa H, Awana V S and Wasa K 2013 J. Appl. Phys. 115 213903
[23] Pan J, Jiao W H, Hong X C, Zhang Z, He L P, Cai P L, Zhang J, Cao G H and Li S Y 2014 arXiv:1404.0371
[24] Singh D J 2014 Phys. Rev. B 90 144501
[25] Fan Q et al 2015 Phys. Rev. B 91 104506
[26] Du Z Y, Feng D L, Wang Z Y, Li Y F, Du G, Yang H, Zhu X Y and Wen H H 2015 Sci. Rep. 5 9408
[27] Werthamer N R, Helfand E and Hohenberg P C 1966 Phys. Rev. 147 295
[28] Tinkham M 1975 *Introduction to Superconductivity*  
(New York: McGraw-Hill)  
[29] Yuan H Q, Singleton J, Balakirev F F, Baily S A, Chen G F,  
Luo J L and Wang N L 2009 *Nature* **457** 565  
[30] Khim S, Lee B, Kim J W, Choi E S, Stewart G R and Kim K H  
2011 *Phys. Rev. B* **84** 104502  
[31] Angst M, Puzniak R, Wisniewski A, Jun J, Kazakov S M,  
Karpinski J, Roos J and Keller H 2002 *Phys. Rev. Lett.* **88** 167004  
[32] Johnston D C 2010 *Adv. Phys.* **59** 803  
[33] Terasaki I, Seiji N, Adachi S and Yamauchi H 1996 *Phys. Rev. B* **54** 11993  
[34] Ashcroft N W and Mermin N D 1976 *Solid State Physics*  
(New York: Holt Rinehart and Winston)  
[35] Padamsee H, Neighbor J E and Shiffman C A 1973 *J. Low Temp. Phys.* **12** 387  
[36] Bouquet F, Wang Y, Fisher R A, Hinks D G, Jorgensen J D,  
Junod A and Phillips N E 2001 *Europhys. Lett.* **56** 856  
[37] Caroli C, Gennes P G and Matricon J 1964 *Phys. Lett.* **9** 307  
[38] Bouquet F, Wang Y, Sheikin I, Plackowski T, Junod A, Lee S  
and Tajima S 2002 *Phys. Rev. Lett.* **89** 257001  
[39] Boaknin E *et al* 2003 *Phys. Rev. Lett.* **90** 117003  
[40] Xu X F *et al* 2013 *Phys. Rev. B* **87** 224507  
[41] Volovik G E 1993 *JETP Lett.* **58** 469