PAPER

Investigating the limits of superconductivity in UTe$_2$

A Weiland, S M Thomas and P F S Rosa

Los Alamos National Laboratory, Los Alamos, NM 87545, United States of America

* Author to whom any correspondence should be addressed.

E-mail: pfsrosa@lanl.gov

Keywords: unconventional superconductivity, actinide materials, disorder

Supplementary material for this article is available online

Abstract

Spin-triplet bulk superconductors are a promising route to topological superconductivity, and UTe$_2$ is a recently discovered contender. The superconducting properties of UTe$_2$, however, vary substantially as a function of the synthetic route, and even nonsuperconducting single crystals have been reported. To understand the driving mechanism suppressing superconductivity, we investigate UTe$_2$ single crystals grown close to the nonsuperconducting boundary (growth temperature $\sim$710 °C) through a combination of thermodynamic and x-ray diffraction measurements. Specific heat measurements reveal a sharp decrease in the superconducting volume and a concomitant increase in the residual specific heat coefficient close to the nonsuperconducting boundary. Notably, these crystals are inhomogeneous and show an apparent double transition in specific heat measurements, similar to samples grown at much higher temperatures ($\sim$1000 °C). Our single crystal x-ray diffraction measurements reveal that there are two important tuning parameters: uranium vacancies and the atomic displacement along the $c$ axis, which shows a twofold increase in samples with a reduced superconducting volume. Our results highlight the key role of local disorder along the uranium-uranium dimers and suggest that the apparent double superconducting transition is more likely to emerge close to the superconducting limits of UTe$_2$.

Spatial inhomogeneity and defects are ubiquitous in quantum materials, yet predictive understanding of interacting electron systems in the presence of disorder remains a grand challenge in condensed matter physics [1, 2]. Unconventional superconducting materials are a particularly intriguing class of quantum materials wherein the effects of disorder have both fundamental and technological importance [3]. In general, nonmagnetic impurities do not break superconducting Cooper pairs in a conventional isotropic $s$-wave superconductor whose superconducting state is mediated by an attractive electron-phonon interaction described by the Bardeen–Cooper–Schrieffer (BCS) model [4]. In an unconventional superconductor that hosts a sign-changing superconducting gap, however, nonmagnetic impurities are expected to strongly suppress superconductivity [5, 6].

Because of strong Coulomb repulsion, electrons in unconventional superconductors tend to pair in higher momentum channels (e.g. $d$-wave and $p$-wave pairing), and superconductivity is stabilized via longer-range interactions such as magnetic fluctuations [7]. The inherent competition between magnetism and superconductivity in these materials therefore favors spatial inhomogeneities that may span nanometer to mesoscopic scales [8–11]. Additional competing instabilities are often observed in unconventional superconductors, including charge-density wave formation in the $d$-wave cuprate superconductors, and electronic nematicity in both $s_{\pm}$-wave iron-based superconductors and $d$-wave heavy-fermion superconductors [12–14]. Singlet superconductivity in these materials is typically enhanced when the competing orders are suppressed [15]. For example, recent scanning tunneling microscopy experiments in FeTe$_{1-x}$Se$_x$ find nanoscale regions of the sample wherein electronic nematicity is enhanced due to anisotropic strain and superconducting coherence peaks are suppressed [16].

Unconventional superconductors that exhibit $p$-wave pairing are seemingly less common [17, 18]. The orbital component of the $p$-wave pair wavefunction is antisymmetric [$\phi(k) = -\phi(-k)$], and odd-parity superconductivity is realized. The spin component in turn supports parallel spins and is called a ‘spin-triplet’
configuration. As pointed out by Anderson, a structure requires inversion symmetry to support a $p$-wave Cooper pair, i.e., $\tilde{\psi}(\mathbf{k}, \uparrow) = -\tilde{\psi}(-\mathbf{k}, \uparrow)$ [19]. For on-site pairing, an odd-parity gap function may therefore emerge in materials whose unit cell contains two $f$ atoms related by inversion symmetry, i.e., the center of inversion is external to the $f$-shell ions [20]. Remarkably, the crystal structures of UPt$_3$, UBe$_{13}$, and newly-discovered UTe$_2$ contain uranium atoms that do not sit at a center of inversion symmetry, and these materials appear to be odd-parity superconductors dominated by antiferromagnetic fluctuations [21–26].

Hund’s coupling, which stems from the Coulomb interaction present in materials with more than one $f$ electron, has been theoretically proposed as a key interaction in enabling odd-parity superconductivity in these structures [27–30].

In addition, $p$-wave superconductors hold the potential to display topological properties when their superconducting state cannot be adiabatically connected to a conventional BCS-type condensate [31, 32]. For instance, the B-phase of superfluid $^3$He, the first unconventional $p$-wave fluid, displays a nontrivial bulk topological invariant in three dimensions and is a prototypical example of time-reversal invariant topological fluid [33, 34]. Importantly, gapless Majorana edge states are predicted to emerge on the surface of bulk topological superconductors, whereas Majorana modes are expected inside their vortex cores. These Majorana modes display non-abelian statistics, a key building block for the realization of quantum computation protected against decoherence [35].

In the case of uranium-based unconventional superconductors, odd-parity superconductivity may be stabilized via two possible routes. First, within the conventional spin-fluctuation theory, ferromagnetic superconductors UGe$_2$, UCoGe, and URhGe arguably enable odd-parity superconductivity due to their proximity to ferromagnetic fluctuations [36, 37]. Second, odd-parity representations may become favorable even in materials close to (or dominated by) antiferromagnetic fluctuations. Recent theoretical developments in this field point to the importance of considering strong spin–orbit coupling, crystal field effects, Hund’s coupling, multiorbital pairing, and sublattice degrees of freedom [30, 38–42].

Materials nearby a ferromagnetic instability have been historically put forward as candidates for odd-parity superconductivity. Sr$_2$RuO$_4$ has been a strong contender for several decades, and its superconducting state was believed to be an odd-parity state that breaks time-reversal symmetry, akin to the A-phase of superfluid $^3$He [43–45]. Electrical transport measurements as a function of chemical composition show that nonmagnetic impurities in Sr$_2$RuO$_4$ quickly suppress superconductivity when the residual resistivity exceeds $1 \mu \Omega \text{cm}$ and the carrier mean free path becomes lower than the superconducting coherence length [46]. This finding supported an unconventional non-$s$-wave pairing for Sr$_2$RuO$_4$. Though the superconducting order parameter of Sr$_2$RuO$_4$ is unconventional, recent nuclear magnetic resonance measurements under uniaxial strain, however, reveal a reduction in Knight shift below $T_c$ that is inconsistent with triplet superconductivity [47, 48].

In this work, we focus on newly-discovered UTe$_2$, a promising candidate for odd-parity topological superconductivity wherein inelastic neutron scattering measurements reveal dominant antiferromagnetic fluctuations [49, 50]. For a review of experimental and theoretical developments in UTe$_2$ in the past few years, we refer the reader to [51]. Here, our goal is to investigate the limits of superconductivity in UTe$_2$ and to identify the main parameters suppressing $T_c$. Through thermodynamic specific heat measurements, we show that the superconducting volume decreases sharply when the optimal growth conditions are only slightly modified. A nearly threefold suppression in the superconducting volume is accompanied by an increase in the residual specific heat coefficient by the same factor. Notably, these crystals also show an apparent double transition in specific heat measurements. In light of structural single crystal x-ray diffraction measurements, we identify three factors associated with the suppression of superconductivity: spatial inhomogeneity, point defects (uranium vacancies), and disorder in the atomic displacement parameter along the $c$ axis.

Single crystals of UTe$_2$ were grown using the chemical vapor transport (CVT) method with iodine as the transport agent as described in [52]. To investigate the limits of superconductivity close to the optimal $T_c$ of $\sim 2 \text{ K}$ [53], the chosen temperature gradient is at or slightly below the previously optimized conditions, i.e., hot end (source) at $800 \text{ C}$ and cold end (sink) at $710 \text{ C}$ [52]. We note that crystals grown in a gradient at even lower temperatures, namely, hot end at $775 \text{ C}$ and cold end at $685 \text{ C}$, do not exhibit a bulk superconducting transition in specific heat measurements. This type of nonsuperconducting samples was previously labeled sample s7 [52] and is also revisited here.

Figure 1 shows the specific heat divided by temperature, $C/T$, as a function of temperature for two superconducting single crystals. In agreement with previous results, sample s6 displays a single transition with a near optimal bulk $T_c$ of 2 K, a normal state specific heat coefficient of $\gamma_N = 121(4) \text{ mJ mol}^{-1} \text{ K}^{-2}$, a residual specific heat coefficient of $\gamma_{SC} = 23 \text{ mJ mol}^{-1} \text{ K}^{-2}$, and a specific heat jump at $T_c$ of $\Delta C / \gamma_N T_c = 1.8$, which is larger than the weak coupling BCS value of 1.43 [52]. In contrast, sample s6b exhibits an apparent split superconducting transition at $T_{c1} = 2.0 \text{ K}$ and $T_{c2} = 1.86 \text{ K}$ and a significantly larger residual specific heat coefficient, $\gamma_{SC} = 67 \text{ mJ mol}^{-1} \text{ K}^{-2}$.
Notably, both the split transition and the sizable $\gamma_{SC}$ that equals roughly half of $\gamma_N$ are observed in crystals previously grown at much higher temperatures, i.e., hot end at 1060 °C and cold end at 1000 °C, closer to the upper formation limit of UTe$_2$ (sample s1 in [52]). At $T_{c1}$, the magnitude of the superconducting jump divided by the normal state Sommerfeld coefficient is only $\Delta C/\gamma_N T_c \sim 0.6$ in sample s6b, which indicates a substantial decrease in the superconducting volume. The decrease in $\Delta C/\gamma_N T_c$ by a factor of about 3 in sample s6b as compared to sample s6 is accompanied by an increase in the residual specific heat coefficient by a similar factor. This correspondence strongly suggests that a significant portion of the volume remains nonsuperconducting in sample s6b and contributes to the residual specific heat coefficient at low temperatures. By taking into account recent muon spin resonance measurements, we argue that the nonsuperconducting volume in UTe$_2$ stems from magnetically inhomogeneous regions of the sample that are slowly fluctuating.

The normal state specific heat coefficient above $T_c$, $\gamma_N$, for sample s6b also appears to increase to $\gamma_N = 129(4)$ mJ mol$^{-1}$ K$^{-2}$, but by a much more modest amount of 6%. As we will see below, this apparent increase is likely related to the presence of uranium vacancies in sample s6b, which causes a decrease in the actual molecular weight of UTe$_2$.

To investigate the key structural tuning parameters responsible for the changes in superconducting properties, we turn to a close structural comparison between samples s6 (single $T_c = 2$ K), s6b (split $T_{c1} = 2.0$ K and $T_{c2} = 1.86$ K), and s7 (no bulk superconductivity). As noted above, we identify three factors associated with the suppression of superconductivity: spatial inhomogeneity, point defects (uranium vacancies), and disorder in the atomic displacement parameter along the c axis.

1. Spatial inhomogeneity

Figure 2 shows the specific heat of samples s6 (panel (a)) and s6b (panel (b)) before and after they were cut into several pieces. The specific heat of each piece is measured individually (solid lines) and compared to the data for the entire crystal (symbols). This experiment, first performed in [54], revealed a substantial variation in the specific heat around the superconducting transition in samples displaying a split transition at $T_{c1} = 1.67$ K and $T_{c2} = 1.46$ K. As mentioned above, these samples were grown at much higher temperatures (i.e., hot end at 1060 °C and cold end at 1000 °C). Importantly, these results have been reproduced by an independent group in [51].

As shown in figure 2(b), a substantial spatial inhomogeneity is also observed in samples grown at lower temperatures that also display a split transition. In addition, the specific heat variation in sample s6b is more pronounced than those in [51, 54] as it occurs even at temperatures away from the superconducting transition, and it affects both the normal state and the residual specific heat coefficients. Here, we again observe the trend of increased residual specific heat as the specific heat jump at $T_c$ decreases.

In contrast, samples with a single transition near optimal $T_c$ are remarkably homogeneous, as shown in figure 2(a). On one hand, these results reveal that thermodynamic measurements in samples displaying split $T_c$ and reduced superconducting volume are an average of inhomogenous regions. On the other hand, electrical or thermal transport measurements may only probe a percolating path within the bulk of these samples.
2. Point defects and lattice parameters

Figure 3(a) shows the superconducting transition temperature, $T_c$, as a function of the unit cell volume, $V = a \times b \times c$, where $a$, $b$, and $c$ are the lattice parameters of the orthorhombic unit cell of UTe$_2$ (space group $Immm$, No. 71). The lattice parameters were determined through single crystal x-ray diffraction at room temperature using a Bruker D8 Venture single-crystal diffractometer equipped with Mo radiation. The fit residuals, $R_1(F^2 > 2\sigma(F^2))$, were 1.5% or smaller for all refinements. The full refinement tables are shown in the supplemental information.

Notably, there is a statistically relevant decrease in the unit cell volumes of samples s6b and sample s7 compared to sample s6. A similar reduction of about 0.2% is observed in both $b$ and $c$ lattice parameters, whereas the $a$ axis does not change within experimental accuracy.

Though this result suggests that the volume contraction is not isotropic, it is informative to calculate the effective pressure generated by the unit cell volume variation extracted from figure 3. Using $B = 64$ GPa as the bulk modulus of UTe$_2$ obtained from $ab initio$ band structure calculations [55], we estimate that samples s7 and s6b experience an effective chemical pressure of $\Delta P = 0.25$ GPa. According to the pressure-temperature phase diagram, 0.25 GPa of hydrostatic pressure would only cause a 0.15 K reduction in $T_c$ [56–58]. Our analysis therefore reveals that chemical pressure is not the dominant tuning parameter in the absence of a superconducting transition in sample s7. Interestingly, this $\Delta T_c$ could explain the reduced transition temperature at $T_{c2} = 1.86$ K in sample s6b. One possible scenario is that small regions of the sample have a reduced unit cell volume due to strains generated during crystal growth.

To unravel the role of point defects on the suppression of superconductivity, we investigate the evolution of $T_c$ as a function of site occupancies in our single crystal x-ray refinements. As shown in figure 3(b), sample s6 (enhanced $T_c$ and superconducting volume) displays a uranium occupancy very close to 100%. Samples s6b and s7, however, contain uranium sites that are not fully occupied. Sample s6b, which shows a split $T_c$ and lower superconducting volume, shows a uranium occupancy of 97%. Sample s7, which has no bulk $T_c$, shows the lowest uranium occupancy, 95%, in agreement with previous reports [59]. We note that we cannot resolve these differences in energy dispersive x-ray spectroscopy measurements, also in agreement with previous reports [52]. These results suggest that uranium point defects, which are at first sight nonmagnetic,
are pair breaking in UTe$_2$ and reduce the magnitude of $T_c$ in sample s7 as expected from the unconventional non-s wave nature of the superconducting state. We note, however, that $T_c$ of sample s6 and the upper transition $T_{c1}$ of sample s6b are identical, which indicates that another parameter is responsible for the reduction in superconducting volume at a given $T_c$.

3. Anisotropic atomic displacements

To shed light on the possible parameters responsible for the reduction in superconducting volume in UTe$_2$, we investigate the evolution of $T_c$ as a function of anisotropic displacement parameters (ADPs) in our single crystal x-ray refinements. It was previously pointed out that the atomic displacement parameters along $a$ and $b$, namely $U_{11}$ and $U_{22}$, respectively, do not show a statistically relevant variation within experimental accuracy for samples s6 and s7, whereas $U_{33}$ shows a subtle increase for the nonsuperconducting sample [52]. Remarkably, sample s6b investigated here reveals a statistically relevant enhancement in displacement disorder along all three directions for all three sites (U, Te1, and Te2), as shown in figure 4.

The most discernible trend again happens in the atomic displacements along the $c$ direction. In sample s6b, $U_{33}$ for the U site is more than two times larger than that in sample s6, which corroborates the presence of increased static disorder along the $c$ direction in samples with reduced superconducting volume. Importantly, we note that the observed variation in $U_{33}$ corresponds to a mean displacement of only 5 pm from the ideal U position and highlights the extreme sensitivity of superconductivity to displacement disorder along $c$.

Because ADPs are a combination of the thermally-induced motion of atoms and static disorder in the lattice, low-temperature x-ray diffraction measurements are needed to reduce thermal displacement and highlight the underlying static disorder.

4. Discussion

Our results, summarized in table 1, reveal that there are multiple pair-breaking parameters playing a role not only on the suppression of the superconducting transition temperature but also on the suppression of the superconducting volume at a given $T_c$. As pointed out previously by Huxley, the evolution of $T_c$ as a function of $1/RRR$ (RRR is the residual resistivity ratio) does not follow the Abrikosov–Gor’kov theory of pair breaking scattering due to nonmagnetic impurities in unconventional superconductors [60]. Here, we confirm that the Abrikosov–Gor’kov theory cannot account for the experimental reduction in $T_c$ as a function of the residual resistivity. Figure 5 shows a compilation of $T_c$ vs $\rho_0$ obtained from [52, 53, 61]. We note that the key data point for the sample exhibiting a bulk superconducting transition at $T_c = 1.1$ K is shown in figure S3 in the supplemental information.
A deviation from the Abrikosov–Gor’kov theory has been observed in many unconventional superconductors including cuprates, iron-based, organic, and heavy-fermion superconductors [62–67]. The origin of this deviation has been explained in terms of forward scattering, Coulomb interactions in multiband systems, strong onsite disorder, a combination of magnetic and nonmagnetic impurities, and spatial variation of the superconducting gap functions. Many of these effects are likely present in UTe$_2$ given the complexity of its band structure, gap function, and disorder effects. Given our current knowledge, we argue that the deviation from the Abrikosov–Gor’kov theory in the regime $\rho_0 \sim 75 \mu\Omega\text{cm}$ stems from the combination of magnetic and nonmagnetic impurities described here as well as the spatial variation of the gap function observed by scanning tunneling spectroscopy measurements [49]. Though it is evident that pair-breaking in UTe$_2$ goes beyond the traditional Abrikosov–Gor’kov theory, the complete suppression of $T_c$ in the regime $\rho_0 > 300 \mu\Omega\text{cm}$ wherein uranium vacancies are present as well as the quick suppression of $T_c$ previously observed in Th-doped samples support the non-$s$-wave character the superconducting state of UTe$_2$ [52].

In summary, we investigate UTe$_2$ single crystals grown from CVT at relatively low temperatures ($\sim 710 ^\circ\text{C}$) close to the nonsuperconducting boundary. Through a combination of thermodynamic specific heat measurements and structural single crystal x-ray diffraction measurements, we show that the superconducting volume decreases sharply when the optimal growth conditions are only slightly modified. The observed threefold suppression in the superconducting volume of sample s6b is accompanied by an increase in the residual specific heat coefficient by the same factor. Sample s6b also shows an apparent double transition in specific heat measurements. We identify three factors associated with the suppression of superconductivity: spatial inhomogeneity, point defects (uranium vacancies), and disorder in the atomic displacement parameter along the $c$ axis. Our results highlight the key role of local disorder in the $c$ directions and suggest that the apparent double superconducting transition is more likely to emerge close to the superconducting limits of UTe$_2$. 

Figure 4. Superconducting transition temperature, $T_c$, as a function of the anisotropic atomic displacement along the $c$ axis in three UTe$_2$ single crystals.
Table 1. Crystal growth parameters and physical/structural properties of UTe$_2$ single crystals investigated in this work.

|                  | Sample 6 | Sample 6B | Sample 7 |
|------------------|----------|-----------|----------|
| $T_c$ (K)        | 2.0      | 1.86 & 2.0| N/A      |
| Growth hot end ($^\circ$C) | 800      | 800$^a$  | 775      |
| Growth cold end ($^\circ$C) | 710      | 710$^a$  | 685      |
| $\gamma_N$ (mJ mol$^{-1}$ K$^{-2}$) | 121(4)   | 129(4)   | 140(10)  |
| $\gamma_{SC}$ (mJ mol$^{-1}$ K$^{-2}$) | 23       | 67       | N/A      |
| $\Delta C/\gamma_N T_c$ | 1.8      | 0.6 (at $T_c$) | N/A      |
| Volume ($\text{Å}^3$) | 356.91(13) | 355.46(10) | 355.48(9) |
| U occupancy (%)  | 99.349   | 96.88     | 94.89    |
| $U U_{33}$ ($\text{Å}^2$) | 0.00     | 683(15)   | 0.00   |

$^a$Sample 6B was grown approximately one year after sample 6 using the same furnace. Nonetheless, the thermocouples and heating element resistances change over time, which results in readings slightly higher than the true zone temperature.

Figure 5. Superconducting transition temperature, $T_c$, as a function of the residual electrical resistivity in UTe$_2$ single crystals. Here, electrical current is applied along the $a$ axis.

5. Methods

Elemental analysis of our single crystals using energy-dispersive x-ray spectroscopy in a commercial scanning electron microscope. Specific heat measurements were made using a commercial calorimeter that utilizes a quasi-adiabatic thermal relaxation technique. Electrical resistivity data were obtained from an AC resistance bridge using a standard four-probe configuration in a commercial cryostat equipped with a $^3$He probe.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

We would like to acknowledge constructive discussions with M O Ajeeh, E D Bauer, M Bordelon, A Huxley, F Ronning, J E Sonier, and J D Thompson. This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Quantum Science Center. Scanning electron microscope and energy dispersive x-ray measurements were performed at the Electron Microscopy Lab and supported by the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy Office of Science. A W acknowledges support from the Los Alamos Laboratory Directed Research and Development program.

ORCID iDs

A Weiland  https://orcid.org/0000-0001-7198-3559
S M Thomas  https://orcid.org/0000-0003-0889-4435
P F S Rosa  https://orcid.org/0000-0002-3437-548X
References

[1] Voit T 2019 Annu. Rev. Condens. Matter Phys. 10 233
[2] Giustino F et al 2020 J. Phys.: Mater. 3 042006
[3] Stewart G R 2017 Adv. Phys. 66 75
[4] Anderson P 1959 J. Phys. Chem. 63 1126
[5] Abrikosov A A and Gor’kov I P 1960 Zhur. Ekspl. i Teoret. Fiz. 39 480–3
[6] Balatsky A V, Vekhter I and Zhu J-X 2006 Rev. Mod. Phys. 78 373
[7] Scalapino D J 2012 Rev. Mod. Phys. 84 1383
[8] Ricci A et al 2011 Phys. Rev. B 84 060511
[9] Park T, Lee H, Martin I, Lu X, Sidovor V A, Go Bryk K, Ronning F, Bauer E D and Thompson J D 2012 Phys. Rev. Lett. 108 077003
[10] Poccia N et al 2012 Proc. Natl Acad. Sci. 109 15685
[11] Campi G and Bianconi A 2021 Condens. Matter 6 40
[12] Chang I et al 2012 Nat. Phys. 8 871
[13] Chu J-H, Analytis J G, Greve K D, McMahon P L, Islam Z, Yamamoto Y and Fisher I R 2010 Science 329 824
[14] Ronning F et al 2017 Nature 548 313
[15] Leroux M et al 2019 Proc. Natl Acad. Sci. 116 10691
[16] Zhao H et al 2021 Nat. Phys. 17 903
[17] Mackenzie A and Maeno Y 2000 Physica B 280 148
[18] Kallin C and Berlinsky J 2016 Rep. Prog. Phys. 79 054502
[19] Anderson P W 1984 Phys. Rev. B 30 4000
[20] Anderson P W 1985 Phys. Rev. B 32 499
[21] Appel G, Goldman A, Shirane G, Bucher E and Lux-Steiner M-C 1987 Phys. Rev. Lett. 58 808
[22] Hiess A, Schneidewind A, Stockert O and Fisk Z 2014 Phys. Rev. B 89 235118
[23] Duan C, Sasmal K, Maple M B, Podlesnyak A, Zhu J-X, Si Q and Dai P 2020 Phys. Rev. Lett. 125 237003
[24] Knafo W, Knebel G, Steffens P, Kaneko K, Rosuel A, Brison J-P, Flouquet J, Aoki D, Lapertot G and Raymond S 2021 Phys. Rev. B 104 L100409
[25] Duan C, Baumbach R E, Podlesnyak A, Deng Y, Moir C, Breindel A I, Maple M B, Nica E M, Si Q and Dai P 2021 Nature 600 636
[26] Butch N P, Ran S, Saha S R, Neves P M, Zic M P, Paglione J, Gladchenko S, Ye Q and Rodriguez-Rivera J A 2022 npj Quantum Mater. 7 39
[27] Norman M R 1994 Phys. Rev. B 50 6904
[28] Norman M R 1994 Phys. Rev. Lett. 72 2077
[29] Hotta T and Ueda K 2004 Phys. Rev. Lett. 92 107007
[30] Hazra T and Coleman P 2022 arXiv:2205.13529
[31] Beenakker C and Kouwenhoven L 2016 Nat. Phys. 12 618
[32] Sato M and Ando Y 2017 Rep. Prog. Phys. 80 076501
[33] Volovik G E 2009 JETP Lett. 90 587
[34] Mizushima T, Tsutsumi Y, Sato M and Machida K 2015 J. Phys.: Condens. Matter 27 113203
[35] Stern A and Lindner N H 2013 Science 339 1179
[36] Takahashi Y 2013 Spin Fluctuation Theory of Itinerant Electron Magnetism vol 253 (Berlin: Springer)
[37] Mineev V P 2017 Phys.-Uspek. 60 121
[38] Chen L, Hu H, Lane C, Nica E M, Zhu J-X and Si Q 2021 arXiv:2112.14750
[39] Kang B, Choi S and Kim H 2022 npj Quantum Mater. 7 64
[40] Kreisel A, Quan Y and Hirschfeld P J 2022 Phys. Rev. B 105 104507
[41] Ishizuka I and Yanase Y 2021 Phys. Rev. B 103 094504
[42] Shishidou T, Suh H G, Brydon P M R, Weinert M and Agterberg D F 2021 Phys. Rev. B 103 104504
[43] Rice T M and Sigrist M 1995 J. Phys.: Condens. Matter 7 L643
[44] Ishida K, Mukuda H, Kitaoka Y, Asayama K, Mao Z Q, Mori Y and Maeno Y 1998 Nature 396 658
[45] Mackenzie A P and Maeno Y 2003 Rev. Mod. Phys. 75 657
[46] Mackenzie A P, Haselwimmer R K W, Tyler A W, Lonzarich G G, Mori Y, Nishizaki S and Maeno Y 1998 Phys. Rev. Lett. 80 161
[47] Postogov A et al 2019 Nature 574 73
[48] Chronister A, Postogov A, Kikugawa N, Sokolov D A, Jerzembeck F, Hicks C W, Mackenzie A P, Bauer E D and Brown S E 2021 Proc. Natl Acad. Sci. 118 e20253118
[49] Jiao L, Howard S, Ran S, Wang Z, Rodriguez J O, Sigrist M, Wang Z, Butch N P and Madhavan V 2020 Nature 579 523
[50] Hayes I M et al 2021 Science 373 797
[51] Aoki D, Brison J-P, Flouquet J, Ishida K, Knebel G, Tokunaga Y and Yanase Y 2022 J. Phys.: Condens. Matter 34 243002
[52] Rosa P F S, Weiland A, Fender S S, Scott B L, Ronning F, Thompson J D, Bauer E D and Thompson J S 2022 Commun. Matter. 3 33
[53] Aoki D et al 2022 arXiv:2206.01363
[54] Thomas S M, Stevens C, Santos F B, Fender S S, Bauer E D, Ronning F, Thompson J D, Huxley A and Rosa P F S 2021 Phys. Rev. B 104 224501
[55] Giord C, Stevens C R, Huxley A, Bauer E D, Santos F B, Thompson J D, Fernandes R M, Zhu J-X, Ronning F, Rosa P F S and Thomas S M 2022 Phys. Rev. B 106 L212101
[56] Braithwaite D, Vališka M, Knebel G, Lapertot G, Brison J-P, Pouret J, Zhitomirsky M E, Flouquet J, Honda F and Aoki D 2019 Commun. Phys. 2 147
[57] Ran S, Kim H, Liu L-L, Saha S R, Hayes I, Metz T, Eo Y S, Paglione J and Butch N P 2020 Phys. Rev. B 101 140503
[58] Thomas S M, Santos F B, Christensen M H, Asaba T, Ronning F, Thompson J D, Bauer E D, Fernandes R M, Fabbris G and Rosa P F S 2020 Sci. Adv. 6 eabc8709
[59] Haga Y, Opletal P, Tokiwa Y, Yamamoto E, Tokunaga Y, Kambe S and Sakai H 2022 J. Phys.: Condens. Matter 34 175601
[60] Huxley A 2021 (Santa Fe, NM)
[61] Aoki D et al 2019 J. Phys. Soc. Japan 88 043702
[62] Graser S, Hirschfeld P J, Zhu L-Y and Dahm T 2007 Phys. Rev. B 76 054516
[63] Analytis J G, Ardavan A, Blundell S J, Owen R L, Garman E F, Jeynes C and Powell B J 2006 Phys. Rev. Lett. 96 177002
[64] Rosa P F S et al 2015 Sci. Rep. 4 6252
[65] Gastiasoro M N, Bernardini F and Andersen B M 2016 Phys. Rev. Lett. 117 257002
[66] Gofryk K et al 2012 Phys. Rev. Lett. 109 186402
[67] Das T, Zhu J-X and Graf M J 2011 Phys. Rev. B 84 134510