Identifying spin-triplet pairing in spin-orbit coupled multi-band superconductors

Christoph M. Puetter\textsuperscript{1} and Hae-Young Kee\textsuperscript{1,2(a)}

\textsuperscript{1} Department of Physics, University of Toronto - Toronto, Ontario M5S 1A7, Canada
\textsuperscript{2} Canadian Institute for Advanced Research, Quantum Materials Program - Toronto, Ontario M5G 1Z8, Canada

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Abstract – We investigate the combined effect of Hund’s and spin-orbit (SO) coupling on superconductivity in multi-orbital systems. Hund’s interaction leads to orbital-singlet spin-triplet superconductivity, where the Cooper pair wave function is antisymmetric under the exchange of two orbitals. We identify three $d$-vectors describing even-parity orbital-singlet spin-triplet pairings among $t_{2g}$-orbitals, and find that the three $d$-vectors are mutually orthogonal to each other. SO coupling further assists pair formation, pins the orientation of the $d$-vector triad, and induces spin-singlet pairings with a relative phase difference of $\pi/2$. In the band basis the pseudospin $d$-vectors are aligned along the $z$-axis and correspond to momentum-dependent inter- and intra-band pairings. We discuss quasiparticle dispersion, magnetic response, collective modes, and experimental consequences in light of the superconductor Sr$_2$RuO$_4$.

Introduction. – Since its inception, standard Bardeen-Cooper-Schriefer (BCS) theory has been considered a classic example for a collective phase emerging from quantum many body effects. However, the discovery of unconventional superconducting phases near antiferromagnetic order in heavy fermion compounds \cite{1,2}, organic materials \cite{3}, and, most recently, Fe-pnictides \cite{4} have exposed the limits of a single-band BCS formulation.

The origin and nature of superconductivity in complex materials where multiple bands cross the Fermi level therefore remains a field of active research, harbouring intriguing challenges and mysteries.

In particular, when the electronic structure near the Fermi energy is composed of different orbitals and spins mixed via spin-orbit (SO) coupling, a pairing symmetry analysis could be non-trivial. For example, a local microscopic interaction such as Hund’s coupling may naturally favour inter-orbital spin-triplet pairing between electrons. However, when orbital and spin fluctuations are significant due to inter-orbital hopping and SO interaction, pairing in definite orbital and spin channels (e.g., spin-singlet or -triplet pairing between electron in orbitals \textit{a} and \textit{b}) is not well defined. Equivalently, from a Bloch band perspective, where the kinetic Hamiltonian including SO effects is diagonal, the decoupling of the microscopic interaction effectively leads to intra- and inter-band pairing with pseudospin-singlet and/or -triplet character.

Below we present a systematic study of how SO and Hund’s couplings jointly give rise to superconductivity in $t_{2g}$ (i.e., $d_{xz}$, $d_{yz}$, and $d_{xy}$) orbital systems. Our findings may apply to a number of multi-orbital $d$-subshell superconductors. To be specific we base our quantitative considerations on the proposed chiral spin-triplet superconductor Sr$_2$RuO$_4$. Here, despite intense investigation for more than a decade, a clear picture for the pairing symmetry, the pairing mechanism and the relevant bands involved that is consistent with all experimental observations has not yet emerged \cite{5,6}.

The paper is organized as follows. In the second section we discuss Cooper pairing in multi-orbital systems. We find that superconductivity from local Hund’s exchange can naturally be characterized by three mutually orthogonal $d$-vectors each describing inter-orbital \textit{even-parity spin-triplet} pairing. We then show how SO coupling pins the orientation of the $d$-vector triad and induces and enhances pairing via coupling to spin-singlet pairing order parameters with a fixed relative phase difference of $\pi/2$. In the third section, we map these local pairing order para-
meters, defined in an orbital and spin basis, to inter- and intra-band pairing in the Bloch band basis. Pairing in the Bloch bands has a strong momentum dependence and the magnitude and direction of the d-vectors depend on the orbital composition at each k-point. In the fourth section, we present the complete self-consistent mean-field (MF) results involving 9 complex order parameters that reproduce the Fermi surface (FS) reported on Sr$_2$RuO$_4$. In addition, the resulting anisotropic quasiparticle (QP) dispersion, the magnetic response and the critical pairing strengths in the presence of SO coupling are considered. We summarize our findings and discuss the relevance for SO-coupled d-orbital superconductors such as Sr$_2$RuO$_4$ in the last section.

**Pairing in SO coupled t$_{2g}$ systems via Hund’s interaction.** — For multi-orbital 3d-subshell systems such as the Fe-pnictides, it was recognized that Hund’s coupling (interaction strength denoted by $J$) is as important as on-site Coulomb repulsion ($U$) [7,8], while SO coupling ($2\lambda$) is relatively weak [9]. In contrast, recent X-ray measurements on 5d transition metal compounds such as Ir-based oxide materials found that the SO interaction of 0.6 eV is roughly comparable to the on-site Coulomb energy [10], suggesting that SO interaction is larger than Hund’s exchange (since $J < U$). Given that the effective pairing interaction in the spin-triplet channel arising from Hund’s coupling and inter-orbital Hubbard repulsion ($V = U - 2J$) scales as $V - J = U - 3J$ (see below), we therefore expect that for 4d-subshell materials such as Sr$_2$RuO$_4$ both SO and spin-triplet pairing interactions are intermediate in strength and of similar magnitude [11–17]. Since neither interaction is negligible nor dominant, we treat both on an equal footing in the present study.

While on-site Hund’s and further neighbor exchange interactions have been recognized to be important for spin-triplet pairing [7,18–21], the combined effect of SO and Hund’s couplings on inter-orbital spin-triplet pairing has not been investigated in t$_{2g}$-orbital systems. To understand superconductivity in SO coupled t$_{2g}$-orbital systems, we consider a generic Hamiltonian $H = H_{\text{kin}} + H_{\text{SO}} + H_{\text{int}}$ consisting of kinetic, SO, and local Kanamori interaction terms. In this section we leave the kinetic Hamiltonian $H_{\text{kin}}$ unspecified and focus on the pairing properties arising from the interplay of the atomic SO coupling $H_{\text{SO}} = 2\lambda \sum_i \mathbf{L}_i \cdot \mathbf{S}_i$ and the local interaction, which, projected on the t$_{2g}$-orbitals, are given by

$$H_{\text{SO}} = i\lambda \sum_{i,\alpha,\beta} c_{i\sigma}^d c_{i\sigma}^d + \sum_{i,\alpha,\beta} \epsilon_{\alpha\beta} c_{i\sigma}^{d\alpha} c_{i\sigma}^{d\beta},$$

$$H_{\text{int}} = \frac{U}{2} \sum_{i,\alpha} c_{i\sigma}^{d\alpha} c_{i\sigma}^{d\alpha} c_{i\sigma}^{d\alpha} c_{i\sigma}^{d\alpha} + \frac{V}{2} \sum_{i,\alpha \neq \beta} c_{i\sigma}^{d\alpha} c_{i\sigma}^{d\beta} c_{i\sigma}^{d\beta} c_{i\sigma}^{d\alpha} + \frac{J}{2} \sum_{i,\alpha \neq \beta} c_{i\sigma}^{d\alpha} c_{i\sigma}^{d\beta} c_{i\sigma}^{d\beta} c_{i\sigma}^{d\alpha}.$$  

Here and in the following, summation over repeated spin indices $\sigma, \sigma' = \uparrow, \downarrow$ is implied while the indices $a, b \in \{xy, xz, yz\}$ belong to an ordered set of t$_{2g}$-orbitals. Furthermore, $\hat{\sigma}^i$ stands for Pauli matrices, $c_{i\sigma}^{at}$ creates an electron on site $i$ in orbital $a$ with spin $\sigma$, and $\epsilon_{\alpha\beta}$ denotes the totally antisymmetric rank-3 tensor. For transparency we have also introduced separate interaction strengths $U, V, J$.

Let us apply a MF approach to study the particle-particle instabilities of the microscopic interaction $H_{\text{int}}$ using the following zero momentum pairing channels:

$$\hat{\Delta}_{a/b}^s = \frac{1}{4N} \sum_k [i\hat{d}^k]^s (c_{a\sigma}^b c_{b\sigma}^b - c_{b\sigma}^b c_{a\sigma}^b),$$

$$\hat{\delta}_{a/b}^j = \frac{1}{4N} \sum_k [i\hat{d}^k]^j (c_{a\sigma}^b c_{b\sigma}^b - c_{b\sigma}^b c_{a\sigma}^b),$$

where $N$ is the number of the $k$ points. Here, $\Delta_{a/b}^s = (\Delta_{a/b}^s)$ (= $\Delta_{a/b}^s$) stands for intra- ($a = b$) and inter-orbital ($a \neq b$) spin-singlet pairing, which is even under the exchange of orbital quantum numbers (i.e. they form “orbital triplets”). The vector order parameter $d_{a/b} = (\langle \hat{d}_{a/b}^s \rangle, \langle \hat{d}_{a/b}^j \rangle) = (\langle \hat{d}_{a/b}^s \rangle)$ on the other hand parametrizes inter-orbital ($a \neq b$) spin-triplet pairing consistent with the usual $d$-vector notation where $i(d \cdot \hat{\sigma}) \hat{\sigma}^j$ describes the spin-triplet pairing gap [2,22]. Note that $d_{a/b}$ is odd under orbital exchange, which is characteristic of an “orbital singlet” (while $d_{a/b} = 0$). Note also that the above order parameters are all even under a parity transformation as they are locally defined; this feature differs in particular from conventional odd-parity spin-triplet pairing where orbital degrees of freedom are absent.

Using the above pairing channels the interaction Hamiltonian takes the form

$$H_{\text{int}} \rightarrow \sum_a \hat{\Delta}_{a/a}^s \hat{\Delta}_{a/a}^s + (V - J) \sum_{a,b} \hat{d}_{a/b}^s \hat{d}_{a/b}^s + J' \sum_{a,b} \hat{\Delta}_{a/b}^s \hat{\Delta}_{a/b}^s + (V + J) \sum_{a,b} \hat{\delta}_{a/b}^j \hat{\delta}_{a/b}^j,$$

where it is clear that only Hund’s coupling can give rise to an instability in a spin-triplet channel [7,19]. We thus
concentrate on the effective pairing interaction
\[ H_{\text{int}} = (U - 3J)N \sum_{a,b,t} \frac{g^{a \dagger b}}{a/b} \frac{d^{a \dagger b}}{a/b} \]

in the attractive regime \( U/3 < J \) (<\( U \)). In general, orbital-singlet spin-triplet pairing can also induce spin-singlet pairing so that the remaining terms in eq. (5) would hamper spin-singlet pairing. However, we assume that their effect is negligible to keep the following self-consistent calculations feasible, and since the induced spin-singlet pairing amplitudes are for the most part smaller than the spin-triplet pairing amplitudes (see below). For notational clarity we label the following inter-orbital pairing only by the three combinations \( a/b = \{xx/xy, yz/xy, yz/zz \} \).

To understand the effect of SO interaction, let us remark on pairing in the absence of SO coupling first. In the case of the layered compound considered below (and for a rather large parameter range) the three spin-triplet \( d \)-vectors \( d_{xz/xy}, d_{yz/xy}, \) and \( d_{xz/zz} \) form a triad of mutually orthogonal vectors with an arbitrary orientation and chirality in spin space, and no relative complex phase difference (hence preserving time reversal symmetry (TRS)). This can be understood by analyzing the Ginzburg-Landau (GL) free energy, which without SO coupling is given by
\[ F \sim \sum_{\nu} \left[ A_{\nu} \left| d_{\nu} \right|^2 + B_{\nu}^{(1)} \left| d_{\nu} \cdot d_{\nu}^* \right|^2 + B_{\nu}^{(2)} \left| d_{\nu} \cdot d_{\nu}^* \right|^2 \right] + \sum_{\nu \neq \kappa} \left[ C_{\nu \kappa}^{(1)} \left| d_{\nu} \cdot d_{\kappa} \right|^2 + C_{\nu \kappa}^{(2)} \left| d_{\nu} \cdot d_{\kappa} \right|^2 \right] + C_{\nu \kappa}^{(3)} \left| d_{\nu} \cdot d_{\kappa} \right|^2 + C_{\nu \kappa}^{(4)} \left| d_{\nu} \cdot d_{\kappa} \right|^2 + C_{\nu \kappa}^{(5)} \left| d_{\nu} \cdot d_{\kappa} \right|^2 \]

up to fourth order, by analogy to He-3 [23]. Here \( \nu, \kappa \) stand for orbital pairs \( a/b \), while the (real) quartic mixing parameters obey \( C_{\nu \kappa}^{(4)} = C_{\kappa \nu}^{(4)} \) and the asymmetry between in-plane and out-of-plane orbitals due to, e.g., inter-orbital hopping is reflected in distinct coefficients \( A_{yz/xy} \neq A_{zx/xy} \), etc.). This form is dictated by gauge symmetry, SU(2) spin rotational symmetry, time reversal symmetry and the underlying lattice symmetries, and shows that the \( C_{\nu \kappa}^{(3)} \) and \( C_{\nu \kappa}^{(4)} \) terms are sensitive to the relative orientation of the \( d \)-vectors, whereas the \( C_{\nu \kappa}^{(1)} \) and \( C_{\nu \kappa}^{(2)} \) contributions additionally depend on their relative complex phases.

However, once SO coupling is included, \( d_{xz/xy}, d_{yz/xy}, \) and \( d_{xz/zz} \) are pinned along \( x, y, \) and \( z \) directions, respectively, as shown in fig. 1. Inversion/time reversal symmetry on the other hand is still preserved and reflected in the degeneracy of the orientations/point groups \( \{d_{xz/xy}, d_{yz/xy}, d_{yz/zz} \} \) and \( \{-d_{xz/xy}, -d_{yz/xy}, -d_{xz/zz} \} \). The pinning of the \( d \)-vectors occurs due to additional terms in the free energy such as \( a^{(1)} \left| d_{yz/xy} \right|^2 + a^{(2)} \left| d_{yz/xy} \right|^2 \) and \( a^{(1)} \left| d_{yz/xy} \right|^2 + a^{(2)} \left| d_{yz/xy} \right|^2 \) where the expansion parameters depend on the SO coupling strength, naively suggesting that \( a^{(1)} \), \( a^{(2)} \) are for the most part the spin-singlet pairing contributions. However, SO interaction further leads to a linear coupling between a particular component of (inter-orbital) spin-triplet pairing and (intra-orbital) spin-singlet pairing. For example, writing SO coupling between \( yz/xy \) and \( xz/xy \) orbitals in the form of \( -i\lambda [\sigma^z]_{\sigma' \sigma} \left( \langle d_{yz/xy}^* d_{yz/xy} \rangle - \langle d_{xz/xy}^* d_{xz/xy} \rangle \right) \) the following linear coupling is allowed in the GL free energy:
\[ -i\lambda \left[ [\sigma^z]_{\sigma' \sigma} \langle \sigma_{\kappa' \sigma} \rangle \right] \left( \langle d_{yz/xy}^* d_{yz/xy} \rangle - \langle d_{xz/xy}^* d_{xz/xy} \rangle \right) + \text{c.c.} \]

Note that the \( d_{yz/xy} \) prefers the \( z \)-direction by coupling to spin-singlet pairing with a relative phase difference of \( \pm \pi/2 \) depending on the sign of \( \lambda \). This is consistent with our findings below that the spin-triplet order parameters are purely real while the spin-singlet amplitudes are purely imaginary. A similar analysis can be carried out for \( d_{zx/zy} \) and \( d_{yz/zy} \). The overall order parameter for \( yz \) and \( xz \) orbitals then is \( \hat{d}_{zx/zy} + i \Delta^s_{y^z/x^z} \). Since the relative phase between the orbital-triplet spin-singlet and the orbital-singlet spin-triplet order parameters is fixed, there should be a collective mode representing a resonance of supercurrent flow between the coupled order parameters with an energy scale of order
\[ \sim \sqrt{\left| \Delta_{s/y^z/x^z} \right|^2 + \left| \Delta_{s/y^z} \right|^2 + \left| \Delta_{s/y^z} \right|^2} \]

Note that the above result is fundamentally different from similar two orbital models, which lead to a single orbital-singlet spin-triplet \( d \)-vector [19,21,24]. The present model is also distinguished from other models where the momentum dependence in the band pairing usually originates from nonlocal momentum dependent interactions [18], whereas here it arises from spin and orbital mixing in the Bloch bands as described next.

Momentum-dependent pairing in the Bloch bands. – Despite having uniform pairing amplitudes \( d_{xz/yz}, d_{yz/xy}, d_{xz/zy}, \Delta^s_{y^z/x^z}, \ldots \), the corresponding inter- and intra-band pairings in the Bloch band basis (now carrying band and pseudospin quantum numbers \( \pm \eta, \rho = \alpha, \beta, \gamma \) and \( s = \pm \)) acquire a strong momentum dependence due to the mixing of orbitals through hopping and SO coupling. To understand how the above local pairing in the orbital and spin basis corresponds to pairing in the Bloch band basis, let us introduce the kinetic Hamiltonian. The most generic kinetic Hamiltonian for

\[ 27010-p3 \]
the experimentally measured FS of Sr. The lying FS obtained from diagonalizing the Hamiltonian consisting of three bands labelled \( \xi_1, \eta, \xi_2 \) with SO interaction, including the QP dispersion and the magnetic response. As discussed in the previous sections the qualitative results are generic for SO coupled \( t_{2g} \) bands (or \( p \)-orbital systems) and can be applied to specific materials such as the single layer ruthenate \( [5,6] \) and the Fe-pnictides \( [7,30] \) using the appropriate band structure.

Using the kinetic Hamiltonian of eq. (10) with a parameter choice mimicking the single layer ruthenate band structure, the MF solutions for various \( \lambda \) are displayed in fig. 3. As one can see, in the absence of SO interaction an orbital-singlet spin-triplet pairing instability develops at a large coupling strength \( 3J - U \gtrsim 1.0 \) for \( d_{x^2-y^2} \) and \( d_{yz/xy} \). Although numerically difficult to resolve, we expect that \( d_{xz/xy} \) and the intra-orbital spin-singlet order parameters simultaneously become finite through quartic or higher order couplings in the Landau free energy zero-momentum pairing. Inter-band pairing in contrast is about an order of magnitude weaker and, in particular for \( \langle \xi_1, \xi_\beta \rangle \), more spread out in momentum space, marking Bloch band states that are energetically still close enough to the FS to participate significantly in pairing.

This analysis demonstrates that inter-orbital pairing arising from Hund’s interaction leads to \( k \)-dependent inter- and intra-band pairing in pseudospin-singlet and and pseudospin-triplet (\( z \)-component only) channels. Furthermore, the pairing instability occurs simultaneously within and between all bands rather than in a single active band with superconductivity leaking into passive bands through, e.g., pair hopping. The role of intra-band spin-triplet pairing between \( \alpha \) and \( \beta \) bands in multi-orbital superconductors like SrRuO\(_4\) has also been the focus of recent studies, where the inter-band order parameter, however, breaks TRS \([27]\) and an intrinsic anomalous Hall effect can contribute significantly to a large TRS breaking signal in Kerr rotation experiments \([28,29]\).
expansion. While the magnitudes of the order parameters depend on the details of the band structure, a robust feature is that finite SO coupling drastically reduces the critical pairing strength. This reduction is mostly facilitated by the additional hybridization provided by $H_{\text{SO}}$, which helps to overcome the momentum mismatch between orbitals/bands near the Fermi level. On the other hand the same mechanism can have a slightly detrimental effect at larger $3J - U$, where the ideal inter-orbital pairing conditions along the diagonals are weakened by the additional hybridization. One may also wonder if the Bogoliubov QP dispersions have anisotropic gaps. The resulting QP bands are shown in fig. 4 and are fully gapped with a fourfold symmetric gap modulation in $k$ space, even though the gap minima are tiny.

Note that the present superconducting state does not break TRS. The magnetic response is a combination of paramagnetic (spin-triplet) and spin-singlet behaviours, with a slightly larger out-of-plane than in-plane total magnetic susceptibility as shown in fig. 5, where $M = (L_z) + 2(S_z)$ is the total magnetization including orbital and spin contributions and $H_B = B \cdot \sum_i (L_z + 2S_z)$ couples the orbital and spin degrees of freedom to the external field $B$. Both orbital and spin expectation values are finite with roughly equal contribution to the total magnetization. For comparison, the normal state magnetizations are also shown in fig. 5 and are larger than in the superconducting state, as expected for a combination of spin-singlet and triplet pairing in the presence of SO interaction. In particular, note that the spin magnetization changes drastically in the superconducting state with increasing $\lambda$. In general, the magnitude of the $d$-vectors, and thus the magnetic response, can be modified by changing the size of the FS sheets. For instance a larger overlap between $yz$ and $xy$ dominated portions of the FS would enhance $d_{yz/xy}$ compared to $d_{xz/xy}$. The spin susceptibility then would be mostly dominated by $d_{yz/xy}$, a situation which may be facilitated by applying uniaxial pressure.

Discussion and summary. – Given that we based our MF study on the Sr$_2$RuO$_4$ compound to illustrate the effect of SO interaction on pairing, let us comment on the compatibility and the limitations of our results with what is known about the superconducting state in Sr$_2$RuO$_4$ [5,6]. Based on the QP gap variation along the FS sheets, one expects that this modulation may also be reflected in orientation sensitive specific heat measurements. Such magnetic field dependent specific heat measurements on Sr$_2$RuO$_4$ have indeed been carried out [31,32], but the interpretation of the experimental results is controversial, making a link to our QP dispersion difficult. However, due to the nature of inter-band pairing, the superconducting state presented here is sensitive to any kind of impurities associated with inter-band scattering, which is consistent with the phenomena observed in Sr$_2$RuO$_4$.

Our result on the magnetization indicates that the spin-susceptibility is finite and different for in-plane and out-of-plane magnetic field orientations in both the normal and the superconducting state, as reported on Sr$_2$RuO$_4$. Yet below $T_c$ the in-plane and out-of-plane susceptibilities decrease, which is in contrast to NMR Knight shift measurements [33,34], which revealed that a change in the spin-response across $T_c$ is absent for any field orientation. This behaviour differs also from the response expected of a chiral $p + ip$ superconductor, where the spin susceptibility decreases for field directions perpendicular to the $a$-$b$ plane but remains constant for parallel orientations. While the amount of change in the present model depends sensitively on the SO interaction strength, as shown in fig. 5, the question also arises as to how orbital and spin contributions were separated to obtain the Knight shift data when SO interaction is significant. Besides this, we note that the magnetic field effect on vortices will be highly non-trivial as well, as it involves competition between various types of vortices including half-quantum vortices [35,36] in the presence of moderate SO coupling.

Finally, the lack of TRS breaking is compatible with the absence of chiral supercurrents as observed in scanning
However, this contrasts with another proposal that the chiral states due to $p + ip$ pairing on $\alpha$ and $\beta$ bands cancel each other leading to a topologically trivial superconductor [27]. It also contradicts Kerr rotation and $\mu$SR measurements which have been interpreted in favour of TRS breaking [39,40]. The issue as to whether TRS is broken or not is not yet resolved in the experimental community. While the current study supports a non-TRS breaking state, it can be modified by going beyond local interactions. A natural extension would be to include the effect of further neighbour ferromagnetic interactions such as those discussed by Ng and Sigrist [18], which could lead to a small admixture of odd-parity pairing with broken TRS in addition to the pairing found here and which may be responsible for the broken TRS signatures found in $\mu$SR and Kerr experiments [39,40]. Another possibility is a finite-momentum pairing state such as a FFLO (Fulde-Ferrell-Larkin-Ovchinnikov) state [41,42]. It is plausible that a FFLO state between different bands can be stabilized over the inter-band pseudospin-triplet pairing. These studies, and more definite predictions for Sr$_2$RuO$_4$ or other specific materials, however, go beyond the scope of the current 9 complex order parameter minimization and require more detailed work.

In summary, we studied the combined effect of Hund’s and SO coupling on $t_{2g}$ orbital systems. Three orbital-singlet spin-triplet pairings were found to form an orthogonal $d$-vector triad. A linear coupling between even-parity inter-orbital spin-triplet and even-parity intra-orbital spin-singlet pairings was allowed due to SO interaction, determining the orientation of the three $d$-vectors and giving rise to a relative phase difference of $\pi/2$ between spin-singlet and spin-triplet order parameters. We also showed that inter-orbital spin-triplet pairing in the orbital basis corresponds to ever-parity inter- and intra-band pairing in the Bloch band basis, and discussed how the pairing strength varies within the Bloch bands. We further found that SO coupling assists Hund’s coupling driven pairing, which generally leads to an anisotropic QP gap and an orbital dependent magnetic response.

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REFERENCES

[1] Grewe N. and Steglich F., *Handbook on the Physics and Chemistry of Rare Earths*, Vol. 14 (North-Holland, Amsterdam) 1991, Chapt. “Heavy Fermions”.

[2] Sigrist M. and Ueda K., *Rev. Mod. Phys.*, 63 (1991) 239.

[3] Powell B. J. and McKenzie R. H., *Rep. Prog. Phys.*, 74 (2010) 103901.

[4] Kamihara Y., J. Am. Chem. Soc., 130 (2008) 3296.

[5] Mackenzie A. F. and Maeno Y., Rev. Mod. Phys., 75 (2003) 657 and references therein.

[6] Kallin C. and Berlinsky J., J. Phys.: Condens. Matter, 21 (2009) 46210 and references therein.

[7] Lee P. A. and Wen X. G., Phys. Rev. B, 78 (2008) 144517.

[8] Yang W. L. et al., Phys. Rev. B, 80 (2009) 014508.

[9] Fazekas P., Lecture Notes on Electron Correlation and Magnetism (World Scientific, Singapore) 1999.

[10] Kuriyama H. et al., Appl. Phys. Lett., 96 (2010) 182103.

[11] Liebsch A. and Lichtenstein A., Phys. Rev. Lett., 84 (2000) 1591.

[12] Pchelkina Z. V. et al., Phys. Rev. B, 75 (2007) 035122.

[13] Mravlje J. et al., Phys. Rev. Lett., 106 (2011) 096401.

[14] Pavarini E. and Mazin I. I., Phys. Rev. B, 74 (2006) 035115.

[15] Malvustuto M. et al., Phys. Rev. B, 83 (2011) 165121.

[16] Rozhicki E. J., Annett J. F., Souquet J. R. and Mackenzie A. P., J. Phys.: Condens. Matter, 23 (2011) 094201.

[17] Haverkort M. W. et al., Phys. Rev. Lett., 101 (2008) 026406.

[18] Ng K. K. and Sigrist M., Europhys. Lett., 49 (2000) 473.

[19] Splek J., Phys. Rev. B, 63 (2001) 104513.

[20] Han J. E., Phys. Rev. B, 70 (2004) 054513.

[21] Dai X., Fang Z., Zhou Y. and Zhang F. C., Phys. Rev. Lett., 101 (2008) 057008.

[22] Leggett A. J., Rev. Mod. Phys., 47 (1975) 331.

[23] Vollhardt D. and Wolflle P., The Superfluid Phases of Helium 3 (Taylor & Francis, London) 1990, Chapt. 5.

[24] Werner R., Phys. Rev. B, 67 (2003) 014505.

[25] Bergemann C. et al., Phys. Rev. Lett., 84 (2000) 2662.

[26] Damascelli A. et al., Phys. Rev. Lett., 85 (2000) 5194.

[27] Raghu S., Kapitulnik A. and Kivelson S. A., Phys. Rev. Lett., 105 (2010) 136401.

[28] Taylor E. and Kallin C., Phys. Rev. Lett., 102 (2009) 157001.

[29] Wysokinski K. I., Annett J. F. and Györrfy B. L., Phys. Rev. Lett., 108 (2012) 077004.

[30] Dagofero M., Nicholson A., Moreo A. and Dagotto E., Phys. Rev. B, 81 (2010) 014511.

[31] Deguchi K., Mao Z. Q. and Maeno Y., J. Phys. Soc. Jpn., 73 (2004) 1313.

[32] Deguchi K., Mao Z. Q., Yagiuchi H. and Maeno Y., Phys. Rev. Lett., 92 (2004) 047002.

[33] Ishida K. et al., Nature, 396 (1998) 658.

[34] Murakawa H. et al., Phys. Rev. Lett., 93 (2004) 167004.

[35] Salomaa M. M. and Volovik G. E., Phys. Rev. Lett., 55 (1985) 1184.

[36] Kee H.-Y., Kim Y. B. and Mari K., Phys. Rev. B, 62 (2000) R9275.

[37] Björnson P. G., Maeno Y., Huber M. E. and Moler K. A., Phys. Rev. B, 72 (2005) 012504.

[38] Kirtley J. R. et al., Phys. Rev. B, 76 (2007) 014502.

[39] Luke G. M. et al., Nature, 396 (1998) 658.

[40] Xia J. et al., Phys. Rev. Lett., 97 (2006) 167002.

[41] Fulde P. and Ferrell R. A., Phys. Rev., 135 (1964) A550.

[42] Larkin A. I. and Ovchinnikov Y. N., JETP, 20 (1965) 762.