Magnetically-textured superconductivity in elemental Rhenium

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Recent μSR measurements revealed remarkable signatures of spontaneous magnetism coexisting with superconductivity in elemental rhenium. Here we provide a quantitative theory that uncovers the nature of the superconducting instability by incorporating every details of the electronic structure together with spin-orbit coupling and multi-orbital physics. We show that conventional s-wave superconductivity combined with strong spin-orbit coupling is inducing even-parity odd-orbital spin triplet Cooper pairs, and in presence of a screw axis Cooper pairs’ migration between the induced equal-spin triplet component leads to an exotic magnetic state.

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Superconductivity is the state of matter in which the electronic wave function spontaneously locks into a value with a definite complex phase. In some unconventional superconductors this form of symmetry breaking is simultaneous with additional breaking of time-reversal symmetry (TRS) indicating that the superconducting state is intrinsically magnetic [1]. Such systems are expected to have important applications in spintronics [2] and topological quantum computing [3] however this is hindered by the lack of a general theory of unconventional superconductivity [4, 5] which is normally associated with strong electron correlations or fluctuations of competing ordered phases. Recently, however, TRS breaking has been reported in seemingly ordinary superconductors where such exotic physics are not at play [6], including the chemical element Rhenium [7]. Here we show that TRS breaking in Re is due to a form of mixed singlet-triplet pairing that has an atomic-scale magnetic texture. Rather than assuming an unconventional pairing interaction from the outset, we couple a conventional pairing model with an ab initio description of the system’s magnetism and electronic structure. We find that a triplet pairing component emerges spontaneously, without further symmetry breaking. When an additional pairing term operating in this channel is added in order to make our theory self-consistent a phase with broken time-reversal symmetry emerges. Through computer experiments we identify the non-symmorphic crystal structure as the key ingredient of this exotic new state. Our approach represents a significant departure from previous attempts at understanding symmetry-breaking in unconventional superconductors, yet it describes experimental data quantitatively with only two adjustable parameters, showing that unconventional superconductivity can be more ubiquitous than hitherto assumed.

The key physical quantity in all known superconductors is the spin-dependent anomalous density \( \chi^{\alpha\beta}(x, y) = \langle \Psi^\alpha(x) \Psi^\beta(y) \rangle \). Here \( \alpha, \beta \) are spin indices and \( \Psi^\alpha(x) \) is the annihilation field operator for an electron with spin \( \alpha \) at \( x \). \( \chi \) plays the role of an order parameter, that is, a quantity that becomes non-zero continuously when entering the ordered (superconducting) phase. Since \( \chi \) represents pairing between two fermions it has to be antisymmetric with respect to the exchange of all the particle labels. It is common to use the Balian-Werthamer parametrisation \( \chi = \sum_{j=S,T,L} \chi^{j} \sigma \chi^{j} \sigma \), where \( \sigma \) and \( \chi^{j} \) represent, respectively, the \( 2 \times 2 \) identity matrix and the \( j \) Pauli matrices. The singlet component of the anomalous density \( \chi^{S} \) and the three triplet components \( \chi^{T}, \chi^{T}, \chi^{T} \) are antisymmetric and symmetric with respect to the exchange of the spin labels and behave as a scalar and a vector under spin rotations, respectively. In mean field descriptions the anomalous density is explained by the spontaneous emergence of a pairing potential \( (d^{S}, d^{T}, d^{T}, d^{T}) \) obeying a self-consistency equation

\[
d^j(x, y) = \sum_{x', y'} \Lambda^{j,j'}(x, y; x', y') \chi^{j'}(x', y')
\]

where the kernel \( \Lambda^{j,j'}(x, y; x', y') \) describes pairing interactions. If the pairing potential is non-trivially complex then the superconducting state breaks TRS. This has been discovered in many superconductors [8, 9] chiefly using muon-spin relaxation (μSR), confirmed in some cases by SQUID magnetometry and/or the optical Kerr effect. Due to the second-order nature of the superconducting phase transition, just below \( T_c \), the pairing potential must be a linear superposition of basis functions of one of the irreducible representations (irreps)
of the crystal space group [31]. Since the identity irrep is always one-dimensional, and therefore cannot lead to a non-trivially complex order parameter, it follows that a pairing potential with the full symmetry of the crystal lattice cannot break TRS. In this picture, TRS breaking at $T_c$ can only be due to a pairing interaction kernel $\Lambda(x,x';y,y')$ favouring a low-symmetry (unconventional) pairing instability or to the fine-tuning of an independent, magnetic instability to coincide with $T_c$ (as special point in the phase diagram of ferromagnetic superconductors [32]). The theory of broken TRS that we present here falls outside both scenarios: on the one hand, our pairing kernel is conventional (i.e. it induces an anomalous density that respects the symmetry of the crystal); on the other hand, the magnetic transition that we find is inextricably linked to the superconductivity - specifically, it relies on a symmetry-preserving, but triplet component of the pairing potential.

In the last few years there is a rising awareness about the internal electronic degrees of freedom like orbitals and sub-lattices in the theory of superconductivity [33-50]: the pairing states depend on these internal degrees of freedom and may result in interesting phenomena like TRS breaking and Bogoliubov surfaces [41].

To describe the superconductivity of Re in a way that captures accurately the effects of multiple orbitals and the crystal structure we use the density functional theory of superconductors [51] extended with relativistic effects [52-53]. In this theory the anomalous density $\chi$ is treated on an equal footing with the electron density $\rho$ and magnetisation $m$. The theory features three potentials $d_{\text{eff}}(x,y)$, $V_{\text{eff}}(x)$, $B_{\text{eff}}(x)$ coupling, respectively, to each of these densities. In principle all three potentials can be determined exactly through variation of an exchange-correlation free-energy functional $\Omega_{xc}[\rho,m,\chi]$. In practice, the functional is not known and approximations have to be made. In our calculations we determine $V_{\text{eff}}(x)$ and $B_{\text{eff}}(x)$ from first principles within the local spin-density approximation (LSDA). This is expected to yield an accurate, ab initio description of the normal-state magnetic and electronic properties together with spin-orbit coupling. To determine the pairing potential $d_{\text{eff}}(x,y)$ we adopt a generic self-consistency equation of the type [1] and make a physically-motivated choice for the interaction kernel. For elemental rhenium the symmetry analysis which could pin down the possible symmetries [31] of the crystal space group is complicated by the multiple orbitals and sub-lattices in the theory of superconductivity [33-50].

The parameter $\Lambda$ is fixed by the known value of the superconducting critical temperature, $T_c = 1.697\pm0.006$K [57] giving $\Lambda = 0.67$ eV. The theory can then be used to predict observable properties. Our treatment is fully relativistic and constrained by the known crystal structure of Re [see Supplement Material IV].
the singlet component at \( T_c \) and does not break any additional symmetries (in other words, our Ginzburg-Landau order parameter remains one-dimensional; the details of the superconducting order parameter structure are given in Supplement III). The singlet-triplet mixing is induced by spin-orbit coupling, similar to the triplet admixture thought to occur in a number of noncentrosymmetric superconductors [58]. While in a single-band picture such admixtures are only possible when the crystal lacks inversion symmetry [59] in a multi-orbital system the possibility exists for centrosymmetric systems as well. Here the SOC leads to orbitally antisymmetric, spin-off diagonal terms of the Hamiltonian which allows the emergence of interorbital (orbitally antisymmetric) triplet pairings (see Supplement II for a detailed discussion).

The presence of this additional component in the anomalous pairing density implies that an additional term needs to be added to our interaction kernel in order to make the theory self-consistent. We thus introduce an additional parameter \( \Lambda \) to make the theory self-consistent. We thus introduce a term needs to be added to our interaction kernel in order (see Supplement II for a detailed discussion).

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The maximum internal magnetic field resulting from this magnetic moment of the rhenium atoms can be estimated by \( B_{\text{int}}^{\text{max}} = \mu_0 \mu_s/(4\pi a_b) \approx 0.06 \text{ mT} \) which is comparable to the value measured experimentally by muons, 0.02 mT [7] (we note as a local probe the muons will typically see a lower value than the maximum estimated). However, due to the zero net magnetic moment we predict that an NMR experiment which could measure the magnetism of the whole unit cell would not detect TRS breaking in the superconducting phase of Re.

A microscopic insight into how this new state comes about can be gained from examination of the zero-temperature quasi-particle density of states (DOS), also shown in Fig. 1. The DOS has multiple superconducting gaps, which is consistent with thermodynamic measurements [23, 64]. However, when resolved by atomic site and spin label we see that these multiple gaps have their origin not in the band structure, but in the magnetic nature of the superconducting state. Specifically, they are due to different gaps in the spin-up and spin-down channels on a given site. Thus, the net magnetic moment on each site can be understood as a result of Cooper pair migration, proposed by Miyake for Sr\(_2\)RuO\(_4\) [65] and thought to occur in LaNiC\(_2\) and LaNiGa\(_2\) [15, 30, 40, 66]; electrons flip their spin to maximise a free-energy advantage awarded to equal-spin Cooper pairs, resulting in unequal Cooper pairing strength in the spin-up and spin-down channels. However, as shown in the figure in the case of Re the effect is reversed between sites 1 and 2, leading to no net magnetisation. We note also that in the present case the pairing takes place principally in the singlet channel, and does not by itself (without migration) break any additional symmetries, while in Refs. [15, 30] the instability is purely triplet and breaks SO(3) symmetry spontaneously, even without Cooper pair migration. Our findings therefore constitute a strong generalisation our understanding of this route to TRS breaking very considerably (we note in passing that pair migration itself can be regarded as a generalisation to Cooper pairs of the Stoner instability, which is the paradigmatic mechanism of TRS breaking for unpaired conduction electrons).

Further insight into the unusual superconducting state of Re can be gained by investigating the phase diagram of our theory as the parameter \( \Lambda \) is varied away from the experimentally-relevant value. This is shown in Fig. 2. The phase diagram shows three distinct thermodynamic phases: a normal state with TRS, a superconducting phase with TRS, and a second superconducting phase.
where the Re sites have finite magnetic moments and which therefore breaks TRS. All the phase boundaries are of second-order which is consistent with all three states possessing different symmetries. The three boundaries meet at a tri-critical point. We note that there is never any magnetism in the normal state, which shows that the broken TRS is inherent to the superconductivity.

The second-order transition between two distinct superconducting phases in the phase diagram of Fig. 2 is a telltale signature of an unconventional superconducting state. We emphasize that the triplet component of the order parameter is finite on either side of that boundary. However, on the high-symmetry side this component is unitary and does not break any additional symmetries, while on the low-symmetry side it becomes non-unitary through Cooper pair migration. This is a generalisation of the coupling of nonunitary triplet pairing to magnetisation discussed in Ref. 15 in the context of LaNiGa$_2$, and that may also apply to the heavy-fermion material UT$_2$ [67], which favours the nonunitary channel of a triplet instability. Our results imply that this mechanism can act through more general types of magnetic order parameter. Another crucial difference is that in the case of Re the unitary triplet pairing is induced by spin-orbit coupling and does not break any additional symmetries. More interestingly based on Fig. 2 one can also identify a region of $\Lambda_{EOT}$ where the transition temperature related to broken TRS is smaller than the superconducting critical temperature.

In line with the above discussion, we may interpret the broken TRS phase as the result of a finite susceptibility to forming a magnetically-textured state that couples to the triplet component of the order parameter. Since broken TRS is not observed in a majority of superconductors, the question remains why Re is particularly susceptible to this type of magnetic order. Given that it involves the breaking of the screw-axis symmetry between the Re1 and Re2 sites, we hypothesise that the crucial ingredient is this non-symmorphic feature of the crystal structure. To test this hypothesis, we have performed two computational experiments where the crystal structure is artificially altered to reduce the effect of this symmetry and the magnetic moment on each Re atom in the ground state is obtained. The results are presented in Fig. 3. In the first computational experiment we enlarge the unit cell in the $z$-direction by creating five copies of each of the two Re atoms, placed at regular intervals in that direction (see figure). The result is equivalent to an infinite stack of 5-atom thick slabs of material where the screw-axis symmetry has been removed, but that symmetry still connects the top atom in one slab to the bottom atom on the next one. We find that the magnetic moment persists at the interface, but it is rapidly suppressed away from it. Moreover, all the moments within a slab point in the same direction, which switches at the interface. This suggests a deep analogy with the theory proposed by Aharata et al. [68] for twin boundaries in time-reversal symmetric non-centrosymmetric superconductors with singlet-triplet admixture, according to which the superconducting state breaks spontaneously the bulk time-reversal symmetry locally near the twin boundary. One can envisage the non-symmorphic structure of Re as an infinite stack of 1-atom thick twin boundaries. This connects the singlet-triplet mixing well known from non-centrosymmetric superconductors [68] to that observed here. In the second computational experiment, the atoms’ distance $d$ from the central $z$-axis is decreased continuously until the screw axis is removed (see figure).

We find that the size of the magnetic moment decreases rapidly as $d$ is reduced and the magnetic moment vanishes completely when it reaches a finite, critical value. This confirms the role of the screw axis in bringing about the broken TRS.

The tri-critical point at $\Lambda_{EOT}^{\text{crit}} \approx 0.26$ eV is an interesting target for future investigations. This value of $\Lambda_{EOT}$ is 31.6% smaller than the experimentally-relevant value for Re. However, there is a large number of Re compounds and alloys that are superconducting, with some showing no signs of broken TRS and others displaying internal fields with a wide range of values [6]. It is therefore likely that a systematic investigation of such compounds may...
Figure 3. Effect of artificially distorted lattice structures. Magnetic moments for the enlarged model system (top figure) and the primitive cell of the model system (bottom figure) where the atoms’ distance from the central axis is decreased step by step until the screw axis is removed.

reveal a rich tri-critical phase diagram. Moreover, on the basis of Fig. 3 (b) we speculate that high pressure measurements may split the two critical temperatures similarly to what was measured in the recent experiments of superconducting Sr$_2$RuO$_4$ [69], offering another route to investigate the tricritical point.

In summary a TRS breaking mechanism was identified in s-wave superconductors with strong spin-orbit coupling and non-symmorphic crystal structure. The orbitally antisymmetric part of SOC induces even-parity triplet Cooper pairs in centrosymmetric systems which may cause TRS breaking if the crystal has a non-symmorphic space group. A quantitative description with two phenomenological parameters could fit the recently available experimental data for rhenium making it the first elemental crystal where signatures of unconventional superconductivity were identified both experimentally [7] and theoretically. The admixed singlet-triplet pairing leading to broken TRS in centrosymmetric systems has much broader implications. Spin- and Angle-Resolved Photo-emission Spectroscopy measurements [70] already suggested the coexistence of spin singlet and spin triplet Cooper pairs in case of Sr$_2$RuO$_4$ (which has centrosymmetric crystal structure) which could be related to the observed Knight shift related to in-plane fields [71]. In the broader context our results imply that superconductivity and magnetism can not be viewed simply as competing order parameters in case of electron-phonon driven s-wave superconductors. In fact, the internal structure of the pairing potential emerging from multiorbital physics has lead to a cooperative interplay between superconductivity and magnetism in the presence of screw-axis together with significant spin-orbit coupling.

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[1] Sudeep Kumar Ghosh, Michael Smidman, Tian Shang, James F Annett, Adrian D Hillier, Jorge Quintanilla, and Huiqiu Yuan, “Recent progress on superconductors with time-reversal symmetry breaking,” Journal of Physics: Condensed Matter 33, 033001 (2020).
[2] Jacob Linder and Jason W. A. Robinson, “Superconducting spintronics,” Nature Physics 11, 307–315 (2015).
[3] Sankar Das Sarma, Michael Freedman, and Chetan Nayak, “Majorana zero modes and topological quantum computation,” npj Quantum Information 1 (2015), 10.1038/npjqi.2015.1.
[4] M. R. Norman, “The challenge of unconventional superconductivity,” Science 332, 196–200 (2011).
[5] D. J. Scalapino, “A common thread: The pairing interaction for unconventional superconductors,” Reviews of Modern Physics 84, 1383–1417 (2012).
[6] Tian Shang and Toní Shiróka, “Time-reversal symmetry breaking in re-based superconductors,” Frontiers in Physics 0 (2021), 10.3389/fphy.2021.651163.
[7] T. Shang, M. Smidman, S. K. Ghosh, C. Baines, L. J. Chang, D. J. Gawryluk, J. A. T. Barker, R. P. Singh, D. McK. Paul, G. Balakrishnan, E. Pomjakushina, M. Shi, M. Medarde, A. D. Hillier, H. Q. Yuan, J. Quintanilla, J. Mesot, and T. Shiróka, “Time-reversal symmetry breaking in Re-based superconductors,” Phys. Rev. Lett. 121, 257002 (2018).
[8] H. R. Ott, H. Rudigier, T. M. Rice, K. Ueda, Z. Fisk, and J. L. Smith, “p-wave superconductivity in uBe$_{13}$,” Phys. Rev. Lett. 52, 1915–1918 (1984).
[9] H. R. Ott, H. Rudigier, Z. Fisk, and J. L. Smith, “Phase transition in the superconducting state of $u_{12}$ $th_{6}be_{113}$ ($x=0$–0.06),” Phys. Rev. B 31, 1651-1653 (1985).

[10] G. M. Luke, A. Kerem, L. P. Le, W. D. Wu, Y. J. Uemura, D. A. Boo, L. Taillefer, and J. D. Garrett, “Muon spin relaxation in UPt$_3$, ” Phys. Rev. Lett. 71, 1466-1469 (1993).

[11] G. M. Luke, Y. Fudamoto, K. M. Kojima, M. I. Larkin, J. Merrin, B. Nachumi, Y. J. Uemura, Y. Maeno, Z. Q. Mao, Y. Mori, H. Nakamura, and M. Sigrist, “Time-reversal symmetry-breaking superconductivity in Sr$_2$RuO$_4$, ” Nature 394, 558-561 (1998).

[12] Andrew Mackenzie and Yoshiteru Maeno, “The superconductivity of Sr$_2$RuO$_4$ and the physics of spin-triplet pairing,” Rev. Mod. Phys. 75, 657-712 (2003).

[13] Y. Aoki, A. Tsuchiya, T. Kanayama, S. R. Saha, H. Sugawara, H. Sato, W. Higemoto, A. Koda, K. Ohashi, K. Nishiyama, and R. Kadono, “Time-reversal symmetry-breaking superconductivity in heavy-fermion PrOs$_4$Sb$_{12}$ detected by muon-spin relaxation,” Phys. Rev. Lett. 91, 067003 (2003).

[14] A. D. Hillier, J. Quintanilla, and R. Cywinski, “Evidence for time-reversal symmetry breaking in the noncentrosymmetric superconductor LaNiC$_2$, ” Phys. Rev. Lett. 102, 117007 (2009).

[15] A. D. Hillier, J. Quintanilla, B. Mazidian, J. F. Annett, and R. Cywinski, “Nonunitary triplet pairing in the centrosymmetric superconductor LaNiGa$_2$, ” Phys. Rev. Lett. 109, 097001 (2012).

[16] Lei Shu, W. Higemoto, Y. Aoki, A. D. Hillier, K. Ohashi, K. Ishida, R. Kadono, A. Koda, O. O. Bernal, D. E. MacLaughlin, Y. Tunashima, Y. Yonezawa, S. Sanada, D. Kikuchi, H. Sato, H. Sugawara, T. U. Ito, and M. B. Maple, “Suppression of time-reversal symmetry breaking superconducting in Pr(Os$_{1-x}$Ru$_x$)$_4$Sb$_{12}$ and Pr$_{1-x}$La$_x$Os$_4$Sb$_{12}$, ” Phys. Rev. B 83, 100504 (2011).

[17] E. R. Schemm, W. J. Gannon, C. M. Wishne, W. P. Halperin, and A. Kapitulnik, “Observation of broken time-reversal symmetry in the heavy-fermion superconductor UPt$_3$, ” Science 345, 190-193 (2014).

[18] J. A. T. Barker, D. Singh, A. Thamizhavel, A. D. Hillier, M. R. Lees, C. Györffy, “Multiple scattering theory for superconducting heterostructures,” Physical Review B 97, 100505 (2018).

[19] A. Bhattacharyya, D. T. Adroja, J. Quintanilla, A. D. Hillier, N. Kase, A. M. Strydom, and J. Akimitsu, “Broken time-reversal symmetry probed by muon spin relaxation in the caged type superconductor Lu$_2$Rh$_7$Sb$_8$, ” Phys. Rev. B 91, 060503 (2015).

[20] A. Bhattacharyya, D. T. Adroja, N. Kase, A. D. Hillier, J. Akimitsu, and Andre Strydom, “Unconventional superconductivity in Y$_2$Rh$_6$Sb$_8$ probed by muon spin relaxation,” Scientific Reports 5, 12926 (2015).

[21] A. Bhattacharyya, D. T. Adroja, N. Kase, A. D. Hillier, A. M. Strydom, and J. Akimitsu, “Unconventional superconductivity in the cage-type compound ScRh$_7$Sb$_8$, ” Phys. Rev. B 98, 024511 (2018).

[22] D. Singh, M. S. Scheurer, A. D. Hillier, and R. P. Singh, “Time-reversal-symmetry breaking and unconventional pairing in the noncentrosymmetric superconductor La$_7$Rh$_6$ probed by $\mu$SR”, Phys. Rev. e-prints, arXiv:1802.01533 (2018), arXiv:1802.01533 [cond-mat.supr-con].

[23] T. Shang, S. K. Ghosh, L. J. Chang, C. Baines, M. K. Lee, J. Z. Zhao, J. A. T. Verezhak, D. J. Gawryluk, E. Pomjakushina, M. Shi, M. Medarde, J. Mesot, J. Quintanilla, and T. Shirou, “Time-reversal symmetry breaking and unconventional superconductivity in Zr$_3$Ir: A new type of noncentrosymmetric superconductor,” arXiv e-prints , arXiv:1901.01414 (2019), arXiv:1901.01414 [cond-mat.supr-con].

[24] J. Zhang, Z. F. Ding, K. Huang, C. Tan, A. D. Hillier, P. K. Biswas, D. E. MacLaughlin, and L. Shu, “Broken time-reversal symmetry in superconducting Pr$_{1-x}$La$_x$Pt$_4$Ge$_{12}$, ” Phys. Rev. B 100, 024508 (2019).

[25] R. P. Singh, A. D. Hillier, B. Mazidian, J. Quintanilla, J. F. Annett, D. McK. Paul, G. Balakrishnan, and M. R. Lees, “Detection of time-reversal symmetry breaking in the noncentrosymmetric superconductor Re$_2$Ir$_2$ using muon-spin spectroscopy,” Phys. Rev. Lett. 112, 107092 (2014).

[26] D. Singh, J. A. T. Barker, A. Thamizhavel, D. McK. Paul, A. D. Hillier, and R. P. Singh, “Time-reversal symmetry breaking in noncentrosymmetric superconductor Re$_2$HF: further evidence for unconventional behaviour in the alpha-Mu family of materials,” ArXiv e-prints (2017), arXiv:1710.08598.

[27] D. Singh, Sajilesh K. P., J. A. T. Barker, D. McK. Paul, A. D. Hillier, and R. P. Singh, “Time-reversal symmetry breaking in the noncentrosymmetric superconductor Re$_2$Ti,” Phys. Rev. B 97, 100505 (2018).

[28] T. Shang, G. M. Pang, C. Baines, W. B. Jiang, W. Xie, A. Wang, M. Medarde, E. Pomjakushina, M. Shi, J. Mesot, H. Q. Yuan, and T. Shirouka, “Nodeless superconductivity and time-reversal symmetry breaking in the noncentrosymmetric superconductor Re$_2$Ti,” Phys. Rev. B 97, 020502 (2018).

[29] Karol Izdryk Wysoki´ nski, “Time reversal symmetry breaking superconductors: SrRuO$_4$ and beyond,” Condensed Matter 4, 47 (2019).

[30] Sudeep Kumar Ghosh, Gábor Csire, Philip Whittlesea, James F. Annett, Martin Gradhand, Balázs Újfalussy, and Jorge Quintanilla, “Quantitative Theory of Triplet Pairing in the Unconventional Superconductor LaNiGa$_2$, ” arXiv e-prints , arXiv:1912.08160 (2019), arXiv:1912.08160 [cond-mat.supr-con].

[31] James F. Annett, “Symmetry of the order parameter for high-temperature superconductivity,” Advances in Physics 39, 83–126 (1990).

[32] A. de Visser, “Superconducting ferromagnets,” in Encyclopedia of Materials: Science and Technology (Elsevier, 2010) pp. 1-6.

[33] Gábor Csire, Balázs Újfalussy, József Cserti, and Balázs Györffy, “Multiple scattering theory for superconducting heterostructures,” Physical Review B 91 (2015), 10.1103/physrevb.91.165142.

[34] Gábor Csire, András Deák, Bendegúz Nyári, Hubert Ebert, James F. Annett, and Balázs Újfalussy, “Relativistic spin-polarized KKR theory for superconducting heterostructures: Oscillating order parameter in the an layer of nb/au/fe trilayers,” Physical Review B 97 (2018), 10.1103/physrevb.97.024514.

[35] Xi Dai, Zhong Fang, Yi Zhou, and Fu-Chun Zhang, “Even parity, orbital singlet, and spin triplet pairing for superconducting LaFeAsO$_1-x$F$_x$, ” Phys. Rev. Lett. 101.
T. Nomoto, K. Hattori, and H. Ikeda, "Classification symmetry in upt multipole superconductivity in multiorbital systems and its implications," Phys. Rev. B 94, 174513 (2016).

P. M. R. Brydon, Limin Wang, M. Weinert, and D. F. Agterberg, "Pairing of j = 3/2 fermions in half-heusler superconductors," Phys. Rev. Lett. 116, 177001 (2016).

Youichi Yanase, "Nonsymmetric weyl superconductivity in upt, based on E2u representation," Phys. Rev. B 94, 174502 (2016).

Emilian M Nica, Rong Yu, and Qimiao Si, "Orbital-selective pairing and superconductivity in iron selenides," npj Quantum Materials 2, 24 (2017).

D. F. Agterberg, P. M. R. Brydon, and C. Timm, "Bogoliubov fermi surfaces in superconductors with broken time-reversal symmetry," Phys. Rev. Lett. 118, 127001 (2017).

P. M. R. Brydon, D. F. Agterberg, Henri Menke, and C. Timm, "Bogoliubov fermi surfaces: General theory, magnetic order, and topology," Phys. Rev. B 98, 224509 (2018).

Wen Huang, Yi Zhou, and Hong Yao, "Exotic cooper pairing in multiorbital models of Sr2RuO4," Phys. Rev. B 100, 134506 (2019).

Aline Ramires and Manfred Sigrist, "Superconducting order parameter of Sr2RuO4: A microscopic perspective," Phys. Rev. B 100, 104501 (2019).

Lun-Hui Wu and Congjun Wu, "Two-band model for magnetism and superconductivity in nickelates," Phys. Rev. Research 1, 032046 (2019).

J. L. Lado and M. Sigrist, "Detecting nonunitary multiorbital superconductivity with dirac points at finite energies," Phys. Rev. Research 1, 033107 (2019).

Han Gyeol Suh, Henri Menke, P. M. R. Brydon, Carsten Timm, Aline Ramires, and Daniel F. Agterberg, "Stabilizing even-parity chiral superconductivity in s2ruo4," Physical Review Research 2 (2020), 10.1103/physrevresearch.2.032023.

Christopher Triola, Jorge Cayao, and Annica M. Black-Schaffer, "The role of odd-frequency pairing in multiband superconductors," Annalen der Physik, 1900298 (2020).

Paramita Dutta, Fariborz Parhizgar, and Annica M. Black-Schaffer, "Superconductivity in spin-3/2 systems: Symmetry classification, odd-frequency pairs, and bogoliubov fermi surfaces," Phys. Rev. Research 3, 033255 (2021).

Yi Li and Congjun Wu, "The j-triplet cooper pairing with magnetic dipolar interactions," Scientific reports 2, 1–5 (2012).

L. N. Oliveira, E. K. U. Gross, and W. Kohn, "Density-functional theory for superconductors," Physical Review Letters 60, 2430–2433 (1988).

K. Capelle and E. K. U. Gross, "Relativistic framework for microscopic theories of superconductivity. i. the dirac equation for superconductors," Physical Review B 59, 7140–7154 (1999).

K. Capelle and E. K. U. Gross, "Relativistic framework for microscopic theories of superconductivity. ii. the pauli equation for superconductors." Physical Review B 59, 7155–7165 (1999).

David R. Smith and P. H. Keesom, "Specific heat of rhenium between 0.15 and 4.0 k," Physical Review B 1, 188–192 (1970).

Gábor Csíre, Stephan Schönecker, and Balázs Újláfyus, "First-principles approach to thin superconducting slabs and heterostructures," Physical Review B 94 (2016), 10.1103/physrevb.94.140502.

Tom G. Saunders, James F. Annett, Balázs Újláfyus, Gábor Csíre, and Martin Gradhand, "Gap anisotropy in multiband superconductors based on multiple scattering theory," Physical Review B 101 (2020), 10.1103/physrevb.101.064510.

L. I. Berger and B. W. Roberts, "Handbook of chemistry and physics," (CRC Press, 2003-2004) Chap. Properties of Superconductors.

M Smidman, M B Salamon, H Q Yuan, and D F Agterberg, "Superconductivity and spin–orbit coupling in non-centrosymmetric materials: a review," Reports on Progress in Physics 80, 036501 (2017).

Ernst Bauer and Manfred Sigrist, eds., Non-Centrosymmetric Superconductors (Springer Berlin Heidelberg, 2012).

J. E. Han, "Spin-triplet s-wave local pairing induced by hund’s rule coupling," Phys. Rev. B 70, 054513 (2004).

Antoine Georges, Luca de Medici, and Jernej Mravlje, "Strong correlations from hund’s coupling," Annual Review of Condensed Matter Physics 4, 137–178 (2013).

Liang Fu and C. L. Kane, "Topological insulators with inversion symmetry," Physical Review B 76 (2007), 10.1103/physrevb.76.045302.

Xiwen Zhang, Qiang Lin, Jun-Wei Luo, Arthur J. Freeman, and Alex Zunger, "Hidden spin polarization in inversion-symmetric bulk crystals," Nature Physics 10, 387–393 (2014).

I-Ming Tang, "The jump in the specific heat of a pure rhenium superconductor as evidence of the two-band effect," Physics Letters A 35, 39–40 (1971).

Kazumasa Miyake, "Theory of pairing assisted spin polarization in spin-triplet equal spin pairing: Origin of extra magnetization in Sr2RuO4 superconducting state," J. Phys. Soc. Jpn. 83, 053701 (2014), https://doi.org/10.7566/JPSJ.83.053701.

Gábor Csíre, Balázs Újláfyus, and James F. Annett, "Nonunitary triplet pairing in the noncentrosymmetric superconductor ianec2," The European Physical Journal B 91, 217 (2018).

Dai Aoki, At Nakamura, Fuminori Honda, DeXin Li, Yoshiya Homma, Yusei Shimizu, Yoshiki J. Sato, Georg Knebel, Jean-Pascal Brison, Alexandre Pourret, Daniel Braithwaite, Gerard Lapertot, Qun Niu, Michal Vališka, Hisatomo Harima, and Jacques Flouquet, "Unconventional superconductivity in heavy fermion UTe2," Journal of the Physical Society of Japan 88, 043702 (2019).

Emiko Arahata, Titus Neupert, and Manfred Sigrist, "Spin currents and spontaneous magnetization at twin boundaries of noncentrosymmetric superconductors," Physical Review B 87 (2013), 10.1103/physrevb.87.220504.

Vadim Grinenko, Shreenanda Ghosh, Rajib Sarkar, Jean-Christophe Orain, Artem Nikitin, Matthias Elender, Debarchan Das, Zurab Guguchia, Felix Brückner, Mark E.
Barber, Joonbum Park, Naoki Kikugawa, Dmitry A. Sokolov, Jake S. Bobowski, Takuto Miyoshi, Yoshiteru Maeno, Andrew P. Mackenzie, Hubertus Luetkens, Clifford W. Hicks, and Hans-Henning Klauss, “Split superconducting and time-reversal symmetry-breaking transitions in Sr2RuO4 under stress,” Nature Physics 17, 748–754 (2021).

[70] C. N. Veenstra, Z.-H. Zhu, M. Raichle, B. M. Ludbrook, A. Nicolaou, B. Slomski, G. Landolt, S. Kitakata, Y. Maeno, J. H. Dil, I. S. Elfimov, M. W. Haverkort, and A. Damascelli, “Spin-orbital entanglement and the breakdown of singlets and triplets in Sr2RuO4 revealed by spin- and angle-resolved photoemission spectroscopy,” Physical Review Letters 112 (2014), 10.1103/physrevlett.112.127002.

[71] A. Pustogow, Yongkang Luo, A. Chronister, Y. S. Su, D. A. Sokolov, F. Jerzembeck, A. P. Mackenzie, C. W. Hicks, N. Kikugawa, S. Raghu, E. D. Bauer, and S. E. Brown, “Constraints on the superconducting order parameter in Sr2RuO4 from oxygen-17 nuclear magnetic resonance,” Nature 574, 72–75 (2019).