Orbital Symmetry and Orbital Excitations in High-$T_c$ Superconductors

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We discuss a few possibilities of high-$T_c$ superconductivity with more than one orbital symmetry contributing to the pairing. First, we show that the high energies of orbital excitations in various cuprates suggest a simplified model with a single orbital of $x^2 - y^2$ symmetry doped by holes. Next, several routes towards involving both $e_g$ orbital symmetries for doped holes are discussed: (i) some give superconductivity in a CuO$_2$ monolayer on Bi2212 superconductors, Sr$_2$CuO$_{4-x}$, Ba$_2$CuO$_{4-x}$, while (ii) others as nickelate heterostructures or Eu$_{2-x}$Sr$_2$NiO$_4$, could in principle realize it as well. At low electron filling of Ru ions, spin-orbital entangled states of $t_{2g}$ symmetry contribute in Sr$_2$RuO$_4$. Finally, electrons with both $t_{2g}$ and $e_g$ orbital symmetries contribute to the superconducting properties and nematicity of Fe-based superconductors, pnictides or FeSe. Some of them provide examples of orbital-selective Cooper pairing.

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I. INTRODUCTION: TOWARDS SUPERCONDUCTIVITY WITH ORBITAL DEGREES OF FREEDOM

Significance of the discovery of high-$T_c$ superconductivity by Bednorz and Muller [1] for recent progress in the quantum many-body theory cannot be overstated — it triggered a huge amount of innovative research on quantum materials and unconventional superconductors, both in the experiment and in the theory. In spite of reaching a qualitative understanding of the nature of the superconducting (SC) state in different transition metal compounds, several open problems remain. Some are related to cuprates, as the astonishing complexity of the theory of cuprate superconductivity was that or- ganic degrees of freedom necessarily come along with strong Jahn-Teller coupling [25, 26], the electron-phonon coupling seems to be essential for SC instabilities in all systems with orbital degeneracy. Nevertheless, to make this review more focused, we shall limit ourselves to the consequences of the orbital degeneracy for the models containing solely electronic degrees of freedom — thus leaving the interplay of the electron-phonon coupling and the orbital degeneracy in the high-$T_c$ superconductors for another work.

The outline of this paper is as follows. One early idea in the theory of cuprate superconductivity was that orbital excitations could contribute to the pairing mechanism, as discussed also in section 2.1, but this was not supported by more recent developments. A usual situation is that the pairing occurs for holes in a single molecular orbital of $x^2 - y^2$ symmetry, see section 2.2. But certainly an interesting question is whether allowing for the presence of holes in both $e_g$ orbitals would not lead to enhanced SC instabilities. This idea has its roots in the Jahn-Teller physics in cuprates [24, 26], as well as in the observation that the propagation of a hole in a Mott (or charge-transfer) insulator is much richer when both $e_g$ orbitals can participate [27]. Partial filling of both $e_g$ orbitals could be realized in the highly overdoped CuO$_2$ monolayer grown on Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$ (Bi2212) [28, 29]. We remark that the symmetry of the SC phase in Bi2212 has been extensively discussed in the literature (see, e.g. [30, 35]).

Furthermore, we emphasize that two-dimensional (2D) systems are special, and possible SC instability was predicted for a layered geometry of NiO$_2$ planes in

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LaNiO$_3$/LaMO$_3$ superlattices [36]. We follow this idea and discuss briefly remarkable similarity between overdoped cuprates and nickelates in sections 3.1 and 3.2. Furthermore, superconductivity occurs also in metallic systems with $t_{2g}$ degrees of freedom, i.e., in planar ruthenate Sr$_2$RuO$_4$ (section 3.3) and in Fe-based superconductors (section 3.4). In the latter systems orbital fluctuations are expected to contribute [8, 37]. The former systems are of particular interest as there spin-orbit interaction entangles spin-orbital degrees of freedom and the orbital states become mixed [38]. A planar iridate Sr$_2$IrO$_4$ with an even stronger spin-orbit coupling shows much of the cuprate phenomenology [39], but no superconductivity was reported so far. This review is summarized in section 4.

II. THE ROLE OF ORBITALS IN SUPERCONDUCTING CUPRATES

A. Earlier theoretical proposals

Following the idea of Jahn-Teller physics in cuprates [26, 27], a question arises how many orbital symmetries should be included in a minimal realistic model for cuprates. Already in the early years of high-$T_c$, the idea of going beyond the single band picture by including O$(2p)$ orbitals in the three-band model has emerged [40–42]. Whether or not the oxygen orbitals could be fully integrated out is still not fully resolved [43–45]. Leaving this issue open, we shall present here an overview of the role played by the copper orbital degrees of freedom.

It has been discussed early on that multiple orbitals contribute to the physical properties of YBa$_2$Cu$_3$O$_{7-x}$ [16, 18] and La$_{2-x}$Sr$_x$CuO$_4$ [49, 50]. The coupling to the lattice was employed as sensitive to the orbital content of wave-functions — multiorbital components were deduced from uniaxial and hydrostatic pressure effects on the value of $T_c$ [51], and from the effect of rhombic distortion on the polarized x-ray absorption spectra in high-$T_c$ superconductors [52].

Further research on stripes and electron-lattice interactions suggested the presence of pseudo-Jahn-Teller effect in cuprates [53–56]. These phenomena follow in a natural way from orbital pseudo-degeneracy [57], and these ideas were further developed in [53–56]. Support for the relevance of electron-phonon interaction comes from the observation of the isotope effect on the pseudo-gap temperature $T^*$ [63], from strong renormalization of certain phonons by doped holes [64], and from recently observed phonon anomalies in charge density wave states in cuprates [55, 56].

Already shortly after the discovery of high-$T_c$ cuprates, it was suggested by Weber [67] that an orbital excitation could be responsible for the pairing. In a typical copper oxide the nearest neighbor Coulomb interaction between holes in the oxygen $p$ orbitals and the Cu $x^2 − y^2$ orbital — such an aspherical Coulomb interaction is estimated to be of the order of 0.3-0.5 eV in the cuprates [67]. Consequently, an excitonic pairing mechanism was proposed: two oxygen holes can gain energy provided that the first one excites the Cu $d$ hole from the $x^2 − y^2$ to the $3z^2 − r^2$ orbital and the second one follows, forming a pair. This mechanism was later further improved by Jarrell, Cox, and others [68, 69] by including the superexchange processes between the nearest neighbor oxygen $p$ orbitals and both Cu $e_g$ orbitals. This latter mechanism was estimated to roughly triple the strength of the coupling between the orbital exciton and the holes on oxygen.

While the above proposal is appealing, unfortunately it is not very realistic: the crucial role played by the copper spins is completely neglected and it is implicitly assumed that the doped holes go to the π-bonding oxygen orbitals. A more realistic two-orbital $e_g$ model was proposed in [27], and the onset of superconductivity in the various versions of the two-orbital Hubbard models was studied in more detail, e.g. in [70–73]. Nevertheless, in order to verify whether these models could be relevant to the cuprate superconductivity, it is crucial to include the size of the crystal-field splitting between the Cu $3z^2 − r^2$ and $x^2 − y^2$ orbitals — as discussed in the next subsection.

B. Orbital excitations in cuprates

In a ‘typical’ high-$T_c$ cuprate, the CuO$_6$ octahedra are elongated along the $c$ axis due to apical oxygen displacements, and the degeneracy of $e_g$ orbitals is lifted. It has been established that both electron-doped and hole-doped copper oxides are strongly correlated electron systems in the vicinity of the metal to charge-transfer insulator transition [74]. One also finds large splitting of the copper $3d$ states and only a single Cu$(3d)−$O$(2p)$ hybridized band crosses the Fermi surface in doped systems. This band has the $x^2 − y^2$ symmetry and becomes half-filled in the undoped charge-transfer insulator La$_2$CuO$_4$. The superexchange stabilizes then antiferromagnetic (AF) order [75] in this and other compounds of the cuprate family [2, 3]. Doping generates a Fermi surface originating from a single band made of oxygen $2p$ and copper $3d$ states, for small hole doping $x < 0.3$, as discussed by Zhang and Rice [76], see Fig. 1. In this regime $d$-wave SC phase is found, and a high value of $T_c$ is obtained when the orbital splitting is large [18, 20].

Interestingly, it has taken almost 20 years both for the experiment and the theory to unequivocally agree on the energies of the (local) orbital excitations on the copper ion of the undoped cuprates (“$d − d$ excitations” [27]). It has long been believed that, while the ground state orbital is of $x^2 − y^2$ character, the energy of the $3z^2 − r^2$ orbital excitation is rather low, for instance of the order of ∼ 0.4 eV — as suggested by the optical and resonant inelastic x-ray scattering (RIXS) measurements of La$_2$CuO$_4$ [77, 78] as well as by optical absorb-
FIG. 1. Schematic phase diagram for cuprates as a function of hole doping $x$, showing the route from the single-band SC phase with holes in $x^2 - y^2$-type molecular orbitals, realized in bulk cuprates (left), to the two-orbital nodeless SC phase in the hole-rich $\text{CuO}_2$/Bi2212 monolayer (right). The insets show the corresponding Fermi surface for one-orbital (left) and two-orbital {$x^2 - y^2$, $3z^2 - r^2$} (right) SC phase. Image is reproduced from [105]; right inset for the hole-rich $\text{CuO}_2$ monolayer is reproduced from [106].

The recent years have, however, lead to substantial advancements both in the resolution of the RIXS experiments of the cuprates [80] as well as ab-initio quantum chemistry calculations [81], and allowed for obtaining the results for cuprates [81, 82] in remarkable agreement between the theory and experiment, as presented in Table I. We emphasize that nowhere one can find the above-mentioned low values of the orbital excitation energies, for all excitations have their energies substantially above 1 eV. Finally, it is only in $\text{La}_2\text{CuO}_4$ that the lowest energy orbital excitation has a $3z^2 - r^2$ character; otherwise this excitation has the highest energy. In general, a more detailed study of various other copper oxides, with / without apical ligands, suggests that the energy of the $3z^2 - r^2$ orbital correlates with the out-of-plane Cu-ligand distance $h$, although this relation is rather complex (cf. Fig. 1 of [81]).

This situation is somewhat more subtle in doped cuprates. Again, in the early years of high-$T_c$ research, it was expected that the occupancy of the low-lying orbital $3z^2 - r^2$ would increase upon doping [47]. However, as just discussed, in ’most’ of the cuprates this orbital turns out to be the highest lying one in the undoped crystals, such a scenario now seems to be no longer relevant. Instead, (typically) the lowest lying $xy$ orbital either hardens by ca. 50 meV [86], or softens by 150 meV [87] with doping, depending on the compound.

TABLE I. The energies of orbital excitations in various undoped cuprates, as obtained from the RIXS experiment [82] (quantum-chemistry calculations [81]). Note that a classical magnetic exchange energy $2J \approx 0.26$ eV is subtracted from all given energy values. Table adopted from [81].

| Cu(3$d$) orbital | $\text{La}_2\text{CuO}_4$ | $\text{Sr}_2\text{CuO}_2\text{Cl}_2$ | $\text{CaCuO}_2$ |
|------------------|--------------------------|--------------------------|------------------|
| $3z^2 - r^2$     | 1.44 (1.37)              | 1.71 (1.75)              | 2.39 (2.38)      |
| $xy$             | 1.54 (1.43)              | 1.24 (1.16)              | 1.38 (1.36)      |
| $xz/yz$          | 1.86 (1.78)              | 1.58 (1.69)              | 1.69 (2.02)      |
Moreover, in both cases the lowest lying \(d-d\) excitation has an energy by ca. 1.5 eV higher than the ground state orbital even in SC samples [88], in agreement with Table I.

The above discussion shows that the orbital excitations in the cuprates have relatively high energies, suggesting that the electrons close to the Fermi surface are clearly of a single \(3d\)-band character. Surprisingly, however, some important signatures of the so-called orbital physics [89–102] are visible there: clear experimental signatures of the collective orbital excitation, the orbiton, have been observed in the quasi-one-dimensional (quasi-1D) copper oxides [97, 98]. To a large extent this turned out to be possible due to the strong crystal-field splitting of the orbital excitations [99, 100]. The search for similar phenomena in the quasi-2D (i.e., high-\(T_c\)) cuprates is ongoing [103].

### III. SUPERCONDUCTIVITY WITH ORBITAL DEGREES OF FREEDOM

#### A. Beyond the cuprates with the pairing in a single \(x^2-y^2\) orbital

A way to enhance the value of \(T_c\) in compounds isostructural with \(La_2CuO_4\) was found by Uchida et al. [104]: higher hole doping in \(CuO_2\) planes is realized by replacing La ions by Sr ions in \(Sr_2CuO_4-\delta\). The SC transition temperature \(T_c = 95\) K is then almost doubled for the hole doping \(x \simeq 0.8\), see Fig. 1. In this regime another nodeless SC phase arises, and the symmetry in the orbital space is partly restored. In fact, also the band of \(3z^2-r^2\) symmetry is partly filled, and the pairing occurs jointly for the \(B_{1g}\) and \(A_{1g}\) channels in \(Sr_2CuO_4-\delta\) and also in \(Ba_2CuO_4-\delta\) [105]. This possibility was discussed a decade ago [106], and was realized, inter alia, in a recently discovered superconductor with \(T_c > 70\) K [107]. The \(CuO_6\) octahedra are compressed here and \(3z^2-r^2\) orbitals contribute at the Fermi surface. The pairing strength is large relative to a similar calculation for an optimally doped Hubbard model. The theory predicts that the pairing strength depends on the shape of the Fermi surface [105], see the right inset of Fig. 1, with nearly square shapes of both electron and hole bands responsible for the enhanced pairing. These results seem to challenge an early view that \(T_c\) is optimized when a single band with \(x^2-y^2\) symmetry crosses the Fermi surface [18–20], see also section 2.

Another way of increasing the hole density in \(Cu(3d)\) orbitals was realized for a \(CuO_2\) monolayer grown on \(Bi2212\) cuprate [28]. Here the \(CuO_2\) monolayer is heavily overdoped by charge transfer at the interface and has a short bond between Cu and the apical O in the substrate. A minimal two-orbital model predicts indeed a nodeless high-\(T_c\) SC state with \(s^\pm\) pairing [29], arising from the spin-orbital exchange a’la Kugel-Khomskii model [89].

#### B. Nickelates

One expects that another route to achieve higher hole doping in \(Cu(3d)\) orbitals is realized in Ni oxides, and indeed the Fermi surface very similar to that for the overdoped cuprates was observed in \(Eu_{2-x}Sr_xNiO_4\) [108]. This Fermi surface is also similar to the one found for \(LaNiO_3/LaAlO_3\) heterostructure, where both \(e_g\) symmetries contribute to the band structure obtained in local density approximation (LDA) [109], see Fig. 2. Although it was argued that the \(3z^2-r^2\) symmetry would be eliminated by electron correlations, both bands were observed in the experiment [108].

The theoretical study of the electronic structure for the \(LaNiO_3/LaAlO_3\) heterostructure suggests that or-
bital engineering using heterostructuring is in principle possible. The electronic structure obtained with LDA for the heterostructure without strain, see Fig. 2(a), has the Fermi surface at $k_z = 0$ very similar to that of the overdoped CuO$_2$ monolayer, cf. Fig. 2(b) and the right inset of Fig. 1. Hence, the theory predicts a SC heterostructure, if this system could be synthesized in the future. So far, widely tunable orbital configurations were indeed realized by in strongly correlated systems: LaTiO$_3$/LaNiO$_3$/LaAlO$_3$ heterostructure [110], and nickelate superlattices [111, 112].

Also in other square-planar nickelate, Pr$_4$Ni$_3$O$_8$, both $e_g$ orbitals contribute to the Fermi surface [113]. X-ray absorption shows that low-spin configuration with $x^2 − y^2$ character of the hole states is realized there [114], making these states remarkably similar to those in hole-doped cuprates. Hence, also these compounds may be considered as promising candidates for unconventional superconductivity. Recently, a family of Ni-based compounds, which contain [Ni$_2$M$_2$O]$_2^-$ (M-chalcogen) layers with an antiperovskite structure constructed by mixed-anion Ni complexes, has been suggested as possible high-$T_c$ superconductors [115]. Here again both $e_g$ symmetries should contribute, and one expects strong competition between $s$-wave and $d$-wave pairing symmetries.

More complicated situations are also possible, and we mention here KNi$_2$S$_2$ as an example of a Ni-based superconductor with three different orbital symmetries contributing at the Fermi surface and a small value of $T_c = 0.46$ K [116]. The electronic structure is described by the multiorbital Hubbard model and this system has certain similarity to iron-based superconductors discussed in section 3.4.

C. Superconducting ruthenate Sr$_2$RuO$_4$

The SC state of strontium ruthenate Sr$_2$RuO$_4$ was discovered in 1994 by Maeno and his collaborators after they had succeeded in synthesizing high-quality samples of the material [117]. It was soon realized that different orbital symmetries contribute to the SC state in this unique ruthenium oxide [118]. The value of $T_c = 1.5$ K is not particularly high, but the ruthenate structure suggests a possible relationship to the high-$T_c$ cuprate superconductors. Yet, in spite of their structural similarity, doped La$_2$CuO$_4$ and Sr$_2$RuO$_4$ are quite different [119].

In conventional superconductors, in high-$T_c$ copper oxides, and in Fe pnictides, the Cooper pairs have even parity. In contrast, Sr$_2$RuO$_4$ is the candidate for odd parity superconductivity [113]. However, the pairing symmetry in this material is not yet fully established (see, e.g. [120, 121]). Ruthenates have active $t_{2g}$ orbital degrees of freedom [122, 123], with degenerate $yz$ and $zx$ orbital states. An additional complication in the theory is the presence of a sizeable spin-orbit coupling ($\zeta \sim 90$ meV at the $\Gamma$ point), which is much smaller than full bandwidth of $\sim 3$ eV but nonetheless leads to important consequences by mixing the low-energy $t_{2g}$ spin-orbital states. As a result, the Fermi surface, consisting of three $\{\alpha, \beta, \gamma\}$ bands [124], changes qualitatively, see Fig. 3(a). In particular, the crossing points (accidental degenera-
cies) between the electronic $\beta$ and $\gamma$ bands vanish and the Fermi surface for both $\{\beta, \gamma\}$ bands becomes more circular \cite{35}, while there is no phase space for mixing of hole-like $\alpha$ band.

For further discussion we focus on the representative $\beta$ band; the mixing of $t_{2g}$ orbital states remains similar for the other bands. The most important consequence of finite spin-orbit coupling $\zeta$ is momentum-dependent spin-orbital entanglement \cite{35} of the eigenstates near the Fermi surface. It is illustrated in Fig. 3(b) for the $\beta$ band and three representative values of momentum $k_z$. Going along the Fermi surface for a fixed value of $k_z$, one observes that not only the orbital character changes, but also both components of $s = 1/2$ spin mix. The latter mixing of spin components is somewhat weaker for large value of $k_z = 3\pi/4$. This mixing plays an important role and the challenging theoretical problem is to include orbital fluctuations in the theory of superconductivity in Sr$_2$RuO$_4$.

When spin-orbit coupling is large enough, it can unify the spin and orbital subspaces locally, forming the effective pseudospin $J_{\text{eff}} = 1/2$ states that dominate low energy physics \cite{93, 125, 126}. This case is particularity relevant for iridium oxides, and indeed, a perovskite compound Sr$_2$IrO$_4$ was found to host pseudospin $J_{\text{eff}} = 1/2$ antiferromagnetism \cite{127, 129}, with quasi-2D magnon excitations similar to those of spin $S = 1/2$ in cuprates. It was recently found that spin-orbit entangled magnetism in iridates and ruthenates is strongly influenced by electron-lattice coupling, via pseudo-Jahn-Teller effect \cite{130}. The remarkable analogy between layered iridates and cuprates holds also upon doping — single band Fermi surface, (pseudo)gap, and Fermi arcs have been detected \cite{131}. However, a long-range coherent superconductivity has not been yet found in iridates. Whether this is related to the fact that spin-orbital excitation energies 0.6 eV \cite{129} in iridates, see Fig. 3(c), are much lower than in cuprates, or to the Mott insulating nature of iridates, in contrast to charge-transfer insulating cuprates, remains an open question. For detailed discussion the similarities and differences between iridates and cuprates, we refer to the recent review article \cite{39}.

D. Iron-based superconductors

Similar to cuprates, the Fe-based superconductors have 2D lattices of $3d$ transition metal ions as building blocks. However, while oxygen ions lie in the same planes as Cu ions in La$_2$CuO$_4$, ions of As, P, or Se lie above or below the Fe plane, in positions close to tetrahedral. For this reason, the out-of-plane As orbitals hybridize well with $t_{2g}$ orbitals of Fe ions. In addition, there is a substantial overlap between the $3d$ orbitals \cite{7, 11, 132, 134}. Under these circumstances, the minimal models for pnictide superconductors contain at least two \cite{135} or three \cite{136} $t_{2g}$ orbitals per Fe atom.

In contrast to undoped cuprates, parent compounds of Fe-based superconductors are metallic \cite{7}, and the pairings of different symmetry compete in a two-band model \cite{11, 137, 139}. The coexistence of hole-like and electron-like bands at the Fermi surface is quite generic \cite{7, 8, 134}. Then Lifshitz transitions can develop for increasing external magnetic field. Such transitions were indeed found in a two-band model with intra-band pairing \cite{140} and could explain the experimental observations in FeSe and Co-doped BaFe$_2$As$_2$ compounds. The competition between different pairing symmetries in KFe$_2$As$_2$ causes a change of symmetry at the critical pressure, from $d$-wave to $s_{++}$-wave symmetry \cite{141}.

Before discussing the nature of pairing, it is interesting to look at the strong coupling model for pnictides, including magnetic frustration \cite{142}. A spin-orbital model for interacting Fe ions in intermediate $S = 1$ spin states was derived \cite{143} in the regime of strong electron correlations. It highlights Hund’s exchange for electron correlations, recently observed experimentally \cite{144}. Magnetic and orbital instabilities are here far richer than in cuprates, and one finds the experimentally observed spin-stripe state which could be accompanied by three different types of orbital order. This is another manifestation of substantial magnetic frustration of the superexchange \cite{142} which may partly explain why magnetic instabilities are sometimes absent, e.g. in FeSe and LiFeAs.

The spin-orbital model \cite{143}, however, does not contain biquadratic exchange which was found to be crucial in magnetism of Fe-based superconductors \cite{145, 148}. This coupling may originate from spin-state fluctuations \cite{149} typical for Fe-ions in systems with strong $p-d$ covalency. While large biquadratic exchange is quite unique and essential for the description of magnetic and nematic instabilities, its implications for SC instabilities belong to open problems in the field. Indeed, the SC phase in iron-based materials occurs in the vicinity of the two above instabilities: Not only one has the usual magnetic phases \cite{150}, but also the nematic order may occur \cite{97, 151, 152}. A detailed study shows that the Fermi surface of FeSe undergoes a spontaneous distortion from fourfold-symmetric to twofold-symmetric elliptical pockets, and next SC phase emerges from the nematic electronic phase.

The theory of Cooper pairing in Fe-based superconductors is rather involved and still far from complete \cite{8, 9, 153}. The role played by orbital and spin fluctuations belongs to challenging open problems in the theory. It was found that the orbital fluctuations may give rise to the strong pairing interaction due to the cooperation of Coulomb and electron-phonon interactions \cite{154, 155}. The theory explains also the famous empirical relation between $T_c$ and the As-Fe-As bond angle \cite{156}.

Altogether, the pairing in iron-based superconductors involves all the five Fe$(3d)$ orbitals, and multiple orbital physics gives rise to various novel phenomena like orbital-selective Mott transition, nematicity, and orbital fluctuations that may support the SC phase. Recent theory treating spin and orbital fluctuations on equal footing...
predicts that, at certain conditions, a spontaneous orbital order sets in first, and then superconductivity follows \cite{157}. The SC gap and low energy excitations in FeSe are dominated by a single \(xz\) orbital \cite{158} which uncovers the orbital origin of the strongly anisotropic gap in the FeSe superconductor \cite{159,162}. In LiFe\(_{1-x}\)Co\(_x\)As spin excitations are orbital selective: low-energy spin excitations are mostly from \(xy\) orbitals, while high-energy spin excitations arise from the \(yz\) and \(zx\) orbitals \cite{163}. Such strongly orbital selective spin excitations in LiFeAs family might play a role in the mechanism of orbital selective Cooper pairing as well.

**IV. SUMMARY**

To conclude, we have presented the current status of the high-\(T_c\) superconductivity in the presence of orbital degrees of freedom. As this subject is very broad, in this review we limit the presentation solely to the electronic degrees of freedom, leaving aside a detailed discussion of the role played by their coupling to the lattice. In case of cuprates large hole doping and removing octahedral distortions is necessary to activate the \(3z^2 - r^2\) orbitals, and we gave examples of cuprates with two \(e_g\) orbitals and higher values of \(T_c\) than in \(La_{2-x}(Sr,Ba)_xCuO_4\). These orbitals contribute to almost the same Fermi surface, consisting of hole and electron parts, also in doped nickelates. But for nickelates we cannot present anything more than a theoretical suggestion that the superconducting instabilities could occur as well. Finally, very interesting superconducting states emerge in \(Sr_2RuO_4\) and in iron pnictides, where several \(t_{2g}\) symmetries meet at the Fermi surface and participate in the Cooper pairing. Search for other transition metal compounds with SC instabilities continues — for instance, recently \(AgF_2\) was suggested as an excellent analogue to \(La_{2}CuO_4\) \cite{164}, but no superconductivity was observed so far.

Summarizing, the presence of orbital degrees of freedom makes high-\(T_c\) superconductors an even more exciting class of quantum materials where the competing quantum phases are of particular importance for superconductivity in layered compounds \cite{165}. It seems that orbital fluctuations could enhance the superconducting transition temperature \(T_c\), but we emphasize that the role of orbital degrees of freedom in the phenomenon of pairing belongs to open problems in the theory; in particular the interplay between orbital degeneracy and the Jahn-Teller coupling to lattice — the idea that guided Bednorz and Müller in their discovery of high-\(T_c\) superconductivity — has to be worked out in a greater detail.

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