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REVIEW ARTICLE

Superconductivity and spin fluctuations

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In the conventional superconductors, the Cooper pairs are mediated by phonons, which is a process where only the correlations between the phonons and the charge properties of the electrons are needed. However, superconductivity can also be derived from other types of elementary excitations. The spin fluctuations are arguably the most promising candidate that can mediate such unconventional superconductivity. In some of the important systems such as cuprates, Fe-based superconductors and heavy-fermion superconductors, spin fluctuations play a key role in the mechanism of their superconductivity although there are still many debates. In this paper, we will give a brief review on the correlation between the spin fluctuations and superconductivity.

Keywords superconductors, magnetism, neutron scattering

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Contents

1 Introduction

In the early days of solid state physics, it was found that the properties of certain materials could be understood by concerning only one aspect of the electrons, either charges or spins. For example, the classical band theory has well explained the difference between metals and insulators in many systems by judging their band filling situations. The magnetic properties of many materials are perfectly described by the Heisenberg model, which only needs the information on the atomic spin arrangements and their couplings. However, such dichotomous view becomes inappropriate with the development of modern condensed matter physics. In many systems that show novel properties, one must consider various factors together including charge, spin, orbit and lattice since they are strongly coupled with each other. The research on superconductivity over the past one hundred years is not an exception and the spin–spin correlations are believed to play an important role in many unconventional superconductors.

In this paper, we will give a brief introduction of the spin fluctuations in various superconductors [1]. Section 2 will introduce the singlet state of the Cooper pairs in the conventional superconductors. Section 3 will review the complicate interaction between superconductivity and magnetism, which includes both the antiferromagnetism (AF) and the ferromagnetism. In addition, some long-range orders are also found to be crucial in understanding many aspects of the unconventional superconductors.

The spin fluctuations are mostly studied by the neutron scattering technique. Specifically, inelastic neutron scattering gives the imaginary part of the dynamical susceptibility $\chi''(Q,\omega)$,

$$\frac{d^2\sigma}{d\Omega d\omega} \propto \frac{F^2(Q)}{1-\exp\left(-\frac{\hbar\omega}{k_B T}\right)}\chi''(Q,\omega) \tag{1}$$

where $d^2\sigma/(d\Omega d\omega)$ is the neutron double-differential cross section into a given solid angle $d\Omega$ with a final energy between E_f and $E_f + d\hbar\omega$, $F(Q)$ the magnetic form factor, k_B the Boltzmann's constant, T the temperature, and $\hbar\omega$ the energy transfer of the excitations where $\hbar$ is the Planck's constant.

2 Spin fluctuations in the conventional superconductors

The conventional superconductors refer to materials whose superconductivity is described by the Bardeen–Cooper–Schrieffer (BCS) theory or its extensions, in which two electrons form Cooper pairs via electron–phonon interactions, i.e., electron–lattice vibrations. Under this mechanism, most superconducting (SC) properties can be understood by concerning the charge property of the electrons alone. However, the spin system is confined in the so-called singlet state. The phase diagram of the conventional superconductors (Type-I) is given in Fig. 1 from the perspective of the spin system. In the normal state, the materials are normal metals in the paramagnetic (PM) or diamagnetic state (DM). When the system enters into the SC state, the wave function of a Cooper pair will not change if the two electrons switch their positions according to the BCS theory. Since its orbital angular momentum is zero ("s-wave"), the two spins of a Cooper pair must be aligned oppositely based on the Pauli exclusion principle. The system is thus in the so-called singlet state denoted as $|0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$.

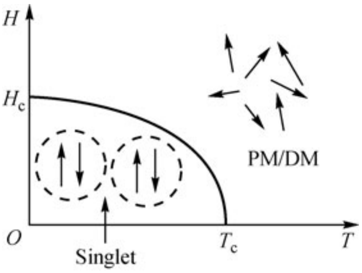

Fig. 1 Schematic phase diagram of the Type-I conventional superconductors from the perspective of spin system.

The singlet state can be measured by the elastic neutron scattering. A magnetic field can induce a moment in the normal state above T_c, which can be measured by polarized neutrons at the nuclear Bragg peaks in the reciprocal space. The spin-part of the induced moment will drop to zero in the SC state since a singlet has a total spin of zero. The results of the neutron scattering experiments clearly show that the spin susceptibility significantly decreases below T_c and thus verify the existence of the singlet state of Cooper pairs [2].

3 Spin fluctuations in the unconventional superconductors

While the properties of the spin system help us to understand the conventional superconductors to some extent, one does not actually need to consider the influence of the spins in comprehending the mechanism and properties of superconductivity. From the 70's of the last century, many new superconductors showing various novel properties were found and their superconductivity cannot be explained by the electron–phonon interactions. In the meantime, the significance of spin system was gradually realized. In most unconventional superconductors, superconductivity happens near the instability of magnetic orders. In some cases, the coexistence of these two orders is also found. It is thus reasonable to assume that spin fluctuations play an important role in the properties of these materials including superconductivity. In conventional superconductors, the materials with higher T_c usually have higher symmetry, but such emperical rule is completely broken since the discovery of the cuprates and other layered superconductors, which may be related to the suppression of magnetic orders in quasi two dimensional systems. The following subsections will give some examples of the interactions between the magnetic correlations and superconductivity.

3.1 Antiferromagnetic correlation and superconductivity

The AF correlations in cuprates are one of the most well studied spin systems. Although there are no consensus on the mechanism of superconductivity, it is generally accepted that spin fluctuations play an important role for superconductivity in cuprates. Figure 2(a) gives the general phase diagram of the hole-doped cuprates [3]. As to the electron-doped materials, the long-ranged ordered AF and SC phases overlap in certain doping range, although it is still under debate whether the coexistence is mesoscopic or microscopic. According to Fig. 2(a), the parent (undoped) compounds are Mott insulators with long-range AF order at low temperature. Introducing holes into the system will quickly increase the conductivity and suppress the AF order at the same time. In some materials like $La_{2-x}Sr_xCuO_4$, certain short-range AF order such as the spin glass may survive at higher doping. The superconductivity appears with further doping and the system shows highest T_c at optimal doping without static AF order coexisting with superconductivity. Since the cuprates have a layered structure, their physical properties are strongly anisotropic between the a–b plane and c axis. The disappearance of the long-range AF order is mainly due to the rapid suppression of the c-axis magnetic correlation with increasing doping.

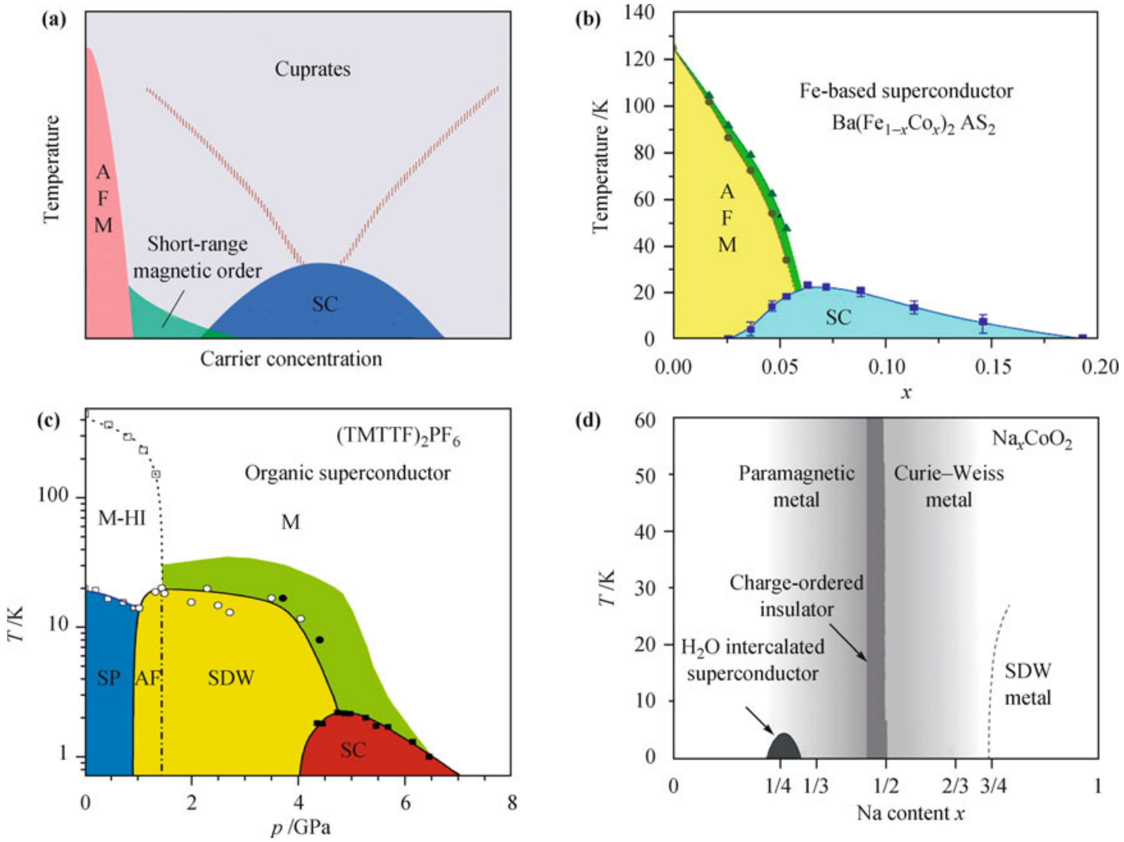

Fig. 2 The phase diagrams of some unconventional superconductors. **(a)** Cuprates [3]. **(b)** Fe-based superconductor $Ba(Fe_{1-x}Co_x)_2As_2$ [29]. **(c)** Organic superconductor $(TMTTF)_2PF_6$ [88]. **(d)** Na_xCoO_2 [91].

However, short-range AF correlations can survive at much higher doping levels. In fact, recent resonant inelastic X-ray scattering experiments suggest that high-energy spin waves in the insulating parent compounds are not affected much by hole-doping that induces metallic state and superconductivity [4]. The AF spin excitations seem to disappear in the heavily overdoped $La_{2-x}Sr_xCuO_4$ where the superconductivity also disappears [5]. It will be important to observe similar results in other families of cuprates.

Among various phenomena of the spin excitations in the superconducting state of the cuprates, the neutron spin resonance or the magnetic resonance is undoubtly the most important feature. The resonance refers to the part of $\chi''(Q,\omega)$ that rapidly increases in the SC state at certain energy [6, 7], forming a peak as shown in Fig. 3(a) [8]. The intensity of the resonance peak decreases with the increasing temperature, showing a kink at T_c, which looks like the order parameter of the SC phase, as shown in Fig. 3(b) [9]. The resonance is also strongly influenced by various methods that affect the SC state, such as doping [8, 10, 11], applying field [12–14], and introducing impurities [15]. Especially, the resonance energy E_r is linear with T_c in most families of the cuprates where the resonance is found [8, 10, 11, 16–20], as shown in Fig. 3(c). The above results suggest that the resonance may indeed be one of the fundamental features that define the high-T_c superconductivity in cuprates.

Another important phenomenon in cuprates is the competition between the AF order and SC order. In the conventional superconductor, the normal state obtained by applying magnetic field below T_c is no different from that above T_c. However, it is found that the magnetic field is able to induce new AF order in the SC state of $La_{2-x}Sr_xCuO_4$ [21], which is either just a kind of short-range AF correlation or a result from some other orders such as striped phase that will be discussed in Section 3.3. In either case, the normal state above the upper critical field H_{c2} at low temperature is certainly different from that above T_c at zero field. This indicates that the energy scales of various orders in cuprates are very close and therefore easily compete with each other.

While there are many results for cuprates, the consensus of the mechanism for superconductivity has not been reached. It is even speculated that the research on high-T_c superconductivity may stop at some point [22]. The recent discovery of the Fe-based superconductors gives us a new hope [23–28, 30]. Their highest T_c ($\sim$ 55 K) is lower than the liquid nitrogen temperature, let alone the maximum T_c of cuprates, but they may lead us to a final conclusion on the mechanism for high-T_c superconductivity since many Fe-based materials show similar properties to those of cuprates. As shown in Fig. 2(b) [29], the parent compound of the Fe-based superconductor

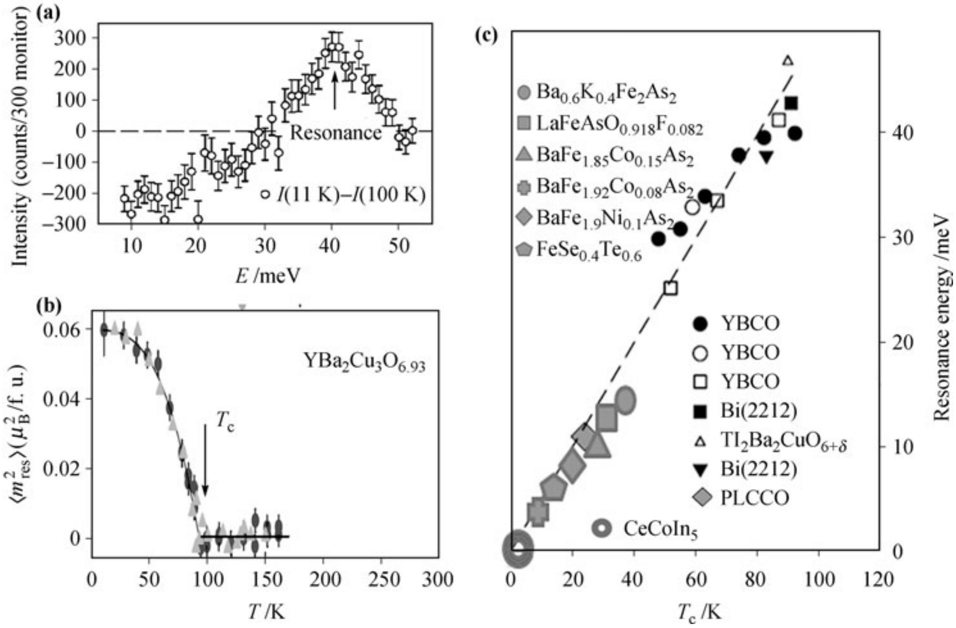

Fig. 3 **(a)** The magnetic resonance in the optimal doped YBCO, which is obtained by the difference between low-temperature (11 K) and high-temperature (100 K) intensities at $Q = (0.5, 0.5, 5)$ [8]. **(b)** The temperature dependence of the intensity of the magnetic resonance in the optimal-doped YBCO [9]. **(c)** The T_c dependence of the resonance energy in various systems including the Fe-based superconductors, cuprates and the heavy fermion superconductor CeCoIn$_5$.

Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ also shows long-range AF order. The superconductivity emerges along with the gradual suppression of the AF order. While other families of the Fe-based materials may have different phase diagrams from Fig. 2(b), the overall picture still holds for most of them [31–37]. The reason that some materials show no long-range AF order without doping is still under debate [38–40]. The Fe–As blocks in these materials are crucial to the understanding of their physical properties, just as the CuO$_2$ planes in cuprates [41]. However, these similarities do not necessarily mean that these two systems are essentially the same. In fact, the band structure [42] and SC pairing symmetry [43, 44] are different from those of the cuprates. Therefore, a detailed experimental study of their similarities and differences will help us to establish the necessary ingredients for high-T_c superconductivity.

In the Fe-based superconductors, there is no general phase diagram as in the case of cuprates [Fig. 2(a)] since the electronic phase diagrams are materials specific [31–37]. The parent compounds of Fe-based superconductors can have different AF structures [45]. However, the neutron spin resonance is found in the SC states of many materials [46–52]. The positions of the resonance in the reciprocal space are the same in spite of their different AF structures in the parent compounds [53]. A recent experiment on the Rb$_2$Fe$_4$Se$_5$ shows that its resonance is at a wave vector different from that in the other systems [52], probably due to the lack of hole pockets in this material [54–57]. The linear dependence of the resonance energy on T_c found in cuprates also holds in the Fe-based superconductors, as shown in Fig. 3(c). The magnetic field can also suppress the resonance and enhance the intensity of the AF order in the underdoped BaFe$_{1.92}$Ni$_{0.08}$As$_2$ [58], but no induced AF order has been found yet in the samples that show no AF order at zero field [59–61].

Besides the cuprates and Fe-based superconductors, the resonance is also found in the heavy-fermion superconductor CeCoIn$_5$ [62]. Roughly speaking, its resonance energy still falls on the linear relationship between E_r and T_c in Fig. 3(c). However, since the T_c of CeCoIn$_5$ is very low ($\sim$ 2.3 K), such intuition may not be correct. In fact, the ratio of E_r/T_c in CeCoIn$_5$ is different from that in the cuprates and Fe-based superconductors. It is suggested that the value of $E_r/(2\Delta)$ where Δ is the superconducting gap is a better scaling factor among these three systems [63].

By summarizing the resonance in the three systems, it is clear that the resonance can occur in either the d-electron SC state or the f-electron SC state. The pairing symmetry of the SC state can be either s-wave or d-wave. Theoretically, the most popular idea for the origin of the resonance is based on the “spin exciton” model, where the resonance is a bound state in the particle-hole channel of the SC state [64]. The scaling of $E_r/(2\Delta)$ is consistent with this model. Interestingly, while the resonance is treated as the spin-triplet state in all theories, there has been no direct evidence for the field-splitting of the resonance in neutron scattering experiments [65].

There are many other heavy-fermion superconductors that exhibit strong AF correlations [66]. However, some of them are difficult to study via neutron scattering due to the difficulty in growing high-quality large single crystals. The heavy-fermion superconductors with AF correlations may be broadly divided into two classes: the superconductivity in the first class materials coexists with the AF order, while it happens near the border of the AF order in the second class materials. The first class of materials can be further divided into the large-moment and small-moment systems. In UPd_2Al_3 and UNi_2Al_3, the magnetic moments are 0.85 μ_B [67] and 0.24 μ_B [69, 70] respectively. Although both materials have large moments, their properties are significantly different. Briefly speaking, the AF oder in UPd_2Al_3 is local and commensurate [67, 68], and superconductivity here is in a spin singlet state [71, 72]. On the contrary, the AF order in UNi_2Al_3 shows itinerant and incommensurate features [69, 70, 73] while its SC state may be spin triplet [74]. In UPd_2Al_3, neutron scattering experiments have shown that its low-energy spin excitations change dramatically across T_c, as shown in Fig. 4(a) [75]. Similar to the above two materials, the superconductivity and antiferromagnetism also coexist in UPt_3 ($T_c = 0.5$ K) [76]. The AF correlation is found below 20 K and the elastic AF order is established below 5 K. However, the moment at each U site is only 0.01–0.03 μ_B, whose origin is still under debate as it is much less than that obtained from the spin fluctuations. The pairing symmetry is also believed to be triplet instead of singlet, which suggests the tendency for ferromagnetic (FM) spin fluctuations although there are no experimental evidence for them [77]. The AF moment of URu_2Si_2 is also very small [78], but this may be due to the chemical phase separation from another large-moment AF system. In UBe_{13}, neutron scattering experiments have also revealed short-range AF correlations below 20 K [79].

The heavy-fermion superconductors whose superconductivity happens at the border of the AF order mainly include $Ce_nM_mIn_{3n+2m}$ (M = Co, Ir, Rh), CeM_2X_2 (M = Cu, Au, Rh, Pd, Ni, and X = Si, Ge), and some other Ce-based materials [66]. Their phase diagrams show significant similarities to that of the cuprates. Figures 4(b) and (c) give the phase diagrams of $CeMIn_5$ (M = Co, Rh, Ir) [80] and $CeCu_2(Si_{1-x}Ge_x)_2$ [81] respectively, where both doping and pressure may lead to superconductivity. Compared to the other Ce-based heavy-fermion superconductors, the T_c's of $Ce_nM_mIn_{3n+2m}$ are higher, which is probably due to their stronger 2D feature that favors the SC pairing [66]. Neutron scattering experiments have shown that AF spin fluctuations are strongly coupled to the superconductivity, such as the

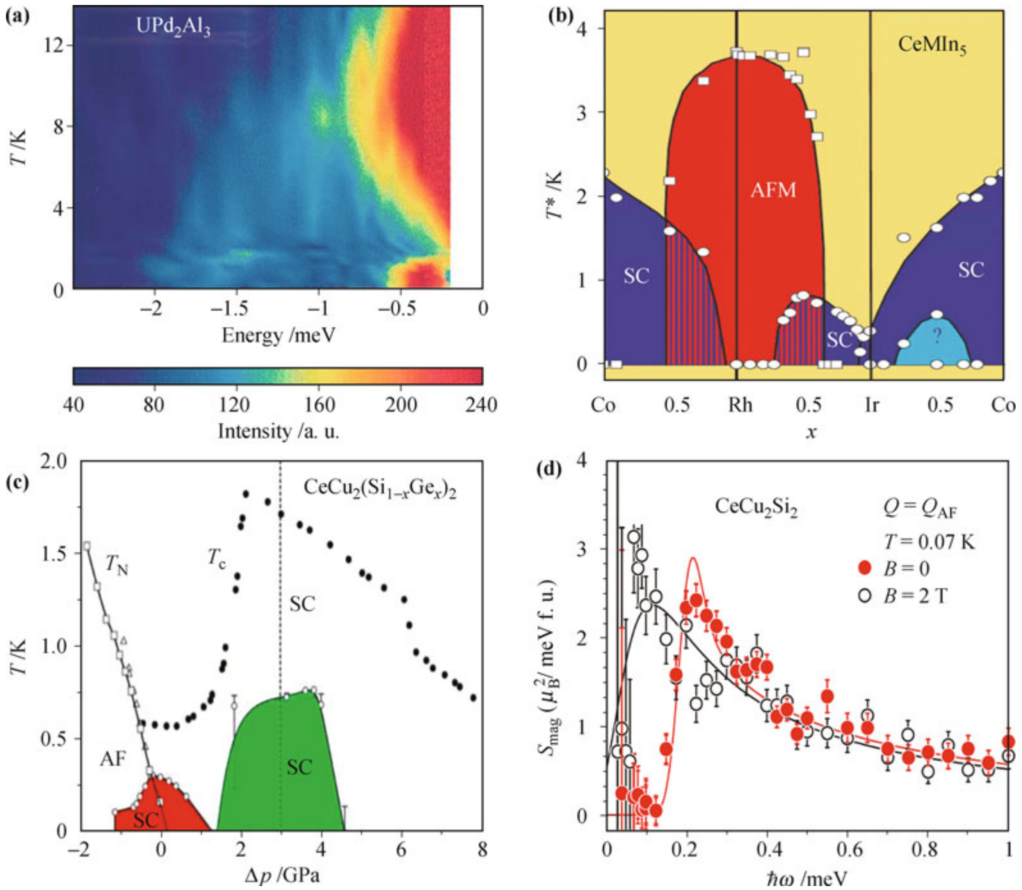

Fig. 4 **(a)** The temperature dependence of the low-energy spin excitations in UPd_2Al_3 shows dramatic changes across T_c [75]. The polarized neutron experiment suggests a spin gap formed in the superconducting state. **(b)** Phase diagram of $CeMIn_5$, where the x is the ratio of left element in the compound [80]. **(c)** Phase diagram of $CeCu_2(Si_{1-x}Ge_x)_2$ under pressure [81]. **(d)** The low-energy spin excitations in $CeCu_2Si_2$ show that the spin gap disappears when the superconductivity is totally suppressed by the magnetic field [82]. The Q_{AF} represents the antiferromagnetic position in the reciprocal space.

resonance in $CeCoIn_5$ [62]. Recently, it is found that the spin excitations in $CeCu_2Si_2$ become gapped in the SC state as shown in Fig. 4(d), where the decrease of the magnetic exchange energy is larger than the SC condensation energy [82]. It should be noted that similar claims have been made for the cuprates too [83, 84].

Another system where AF correlations may play an important role in superconductivity is the organic superconductors [85]. Historically, the one-dimensional organic superconductors have been thought to be a major candidate for high-temperature or even room-temperature superconductivity [86]. While the T_c's of (quasi) one-dimensional organic superconductors are much lower than the expected values, their physical properties are quite interesting. Figure 2(c) gives the phase diagram of $(TMTTF)_2PF_6$ [88], whose ground state changes from the AF to SC state with increasing pressure. The later-discovered two-dimensional superconductor κ-$Cu[N(CN)_2]Cl$ also shows superconductivity near the AF order [87]. In both the one- or two-dimensional superconductors, the ground states can be easily varied by external factors such as magnetic field and pressure [85]. More recently, superconductivity has been found in doped organic crystals containing an extended phenanthrene-like structural motif [89, 90]. It is thus helpful to test some fundamental physical concepts in the organic superconductors. Unfortunately, few inelastic neutron scattering experiments have been done due to the small size of the samples, and the magnetic moment, the large nuclear lattices, and the issues of incoherent scattering from hydrogen atoms.

The correlation between the AF and superconductivity is also observed in the intercalated superconductors, where the superconductivity is reversibly introduced by intercalating certain elements within the atomic layers of the materials. For example, the system shows distinct phases with increasing Na content in Na_xCoO_2 [Fig. 2(d)] [91] including the spin-density waves (SDW) at high Na doping level. The superconductivity only appears with water intercalation for the Na doping of $1/4 < x < 1/3$. Although weak AF and FM spin excitations have been found in the water-free samples, no evidence is shown in the SC samples [92]. Due to the difficulty in growing SC samples, no significant progress has been made. In another intercalated SC system of alkali-metal doped β-MNX ($M = \mathrm{Ti, Zr, Hf}$; $X = \mathrm{Cl, Br, I}$) with the highest T_c of 25 K, the spin fluctuations may be directly associated with superconductivity [93]. Unfortunately, there is no inelastic neutron scattering experiments on this system.

3.2 Ferromagnetic correlation and superconductivity

In conventional superconductors, superconductivity and FM order cannot coexist since the latter favors the triplet pairing which tends to break the singlet state of the Cooper pairs. Indeed, magnetic impurities can easily destroy superconductivity in conventional superconductors. However, in some unconventional superconductors, the FM correlations may contribute to superconductivity if the pairing is triplet.

The FM spin fluctuations are found in some heavy-fermion superconductors. As in the case of AF materials, these materials can also be divided into two catalogs: the one where superconductivity coexists with ferromagnetism and the one that superconductivity happens at the border of the FM order. Figure 5(a) [94] gives the phase diagram of UGe_2 that belongs to the first class, where the ground state is FM at zero pressure. Although its f electrons show strong local-moment characteristic, it is also found that the FM state exhibits an itinerant feature [95–98]. Superconductivity appears when the FM order is partially suppressed by pressure [94]. Transport measurements have shown that some physical properties change below T_x, which is below the Curie temperature T_c [97, 99–102], which suggest that the density of states increases around T_x. It is found that the system is in the FM state either below or above T_x, but a larger moment is found in the FM2 state [103]. The competition between FM1 and FM2 may be associated with the orbital magnetism [104]. The intensities of the magnetic Bragg peaks do not change when the system enters into the SC

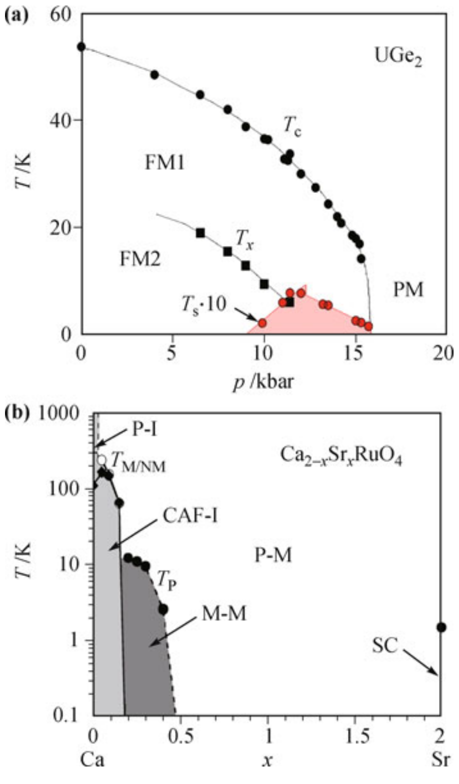

Fig. 5 **(a)** Phase diagram of the heavy fermion superconductor UGe_2 under pressure, where T_s and T_c are the superconducting transition temperature and Curie temperature of FM1 state respectively [94]. **(b)** Phase diagram of $Ca_{2-x}Sr_xRuO_4$ where superconductivity is only found in pure Sr_2RuO_4 [115].

state [97, 105, 106]. The mechanism of the coexistence of superconductivity and FM order is still at disputes. URhGe shows similar phenomena with a quantum critical point [107]. The second class includes UCoGe [108] and UIr [109], whose superconductivity happens near the FM border. Recent inelastic neutron scattering experiments on UCoGe [110] reveal a significant anisotropy of the magnetic correlation length in spin excitations, in constrast to the almost isotropic length for UGe_2.

After the discovery of $La_{2-x}Sr_xCuO_4$, it was found that the isostructural compound Sr_2RuO_4 is also superconducting [111]. However, further experiments revealed that its superconductivity is different from that of the cuprates. The pairing symmetry is *p*-wave [112, 113], therefore a small amount of impurities can totally suppress its superconductivity [114]. The system shows a complicated phase diagram upon Ca-doping, as shown in Fig. 5(b) [115]. Although a long-ranged AF order is found in the heavily doped regime, it is the FM spin fluctuations that are believed to be associated with superconductivity. Neutron scattering experiments have found incommensurate spin fluctuations in pure Sr_2RuO_4 [116]. It is further revealed that a competition between AF and FM spin fluctuations exist at $0.2 \leqslant x \leqslant 1.5$ in $Ca_{2-x}Sr_xRuO_4$ [117]. At present, there are no evidences for a neutron spin resonance for system.

In the heavily investigated iron-based superconductors [118], the parent compounds for all superconductors are ordered antiferromagnetically except for LiFeAs [45], which has been suggested as being close to a FM instability [119]. However, recent inelastic neutron scattering experiments on superconducting [120, 121] and nonsuperconducting LiFeAs [122] show that spin excitations in this material are close to AF ordering wave vector instead of FM ordering wave vector.

3.3 Magnetic order and other orders

As discussed in the above sections, both the AF and FM spin fluctuations may play important roles in unconventional superconductivity. However, it often happens that other long-ranged orders may compete with the magnetic order. We give several examples in this section.

In $La_{2-x}Ba_xCuO_4$, while the T_c shows a parabolic dependence with doping, an anomaly occurs at $x=1/8$ where the T_c almost goes to zero. It is later found that this is related to the so-called "striped phase", where the holes doped into the parent compounds tend to align with each other, forming one-dimensional rivers inside an AF insulating background to minimize the energy, as shown in Fig. 6(a). Such a phase gives rise to the incommensurate peaks in the reciprocal space [123]. The incommensurability increases with increasing doping and T_c [124]. The spin excitations in this system exhibit an hourglass dispersion as shown in Fig. 6(b) [125], where the low-energy spin excitations come from the correlation between the spin stripes while the intra-stripes correlation gives the high-energy spin excitations. Interestingly, such hourglass dispersion is also found in the well superconducting $La_{2-x}Sr_xCuO_4$ and other families of cuprates [125]. It is possible that the stripes rapidly fluctuate and thus give no static order. On the other hand, the Fermi nesting picture based on the *d*-wave pairing symmetry can also explain the incommensurate peaks and hourglass dispersion [126, 127]. Currently, it is still under debate which microscopic scenario is correct.

A concept closely related to the striped phase is the so-called "nematic phase" [128], which is borrowed from the field of liquid crystals. The static striped phase may be thought of as the "smectic phase" in the liquid crystals, where the translation symmetry is broken along only one particular direction. Changing some parameters like doping will tune the smectic phase into the nematic phase, which only breaks the four-fold rotational symmetry of the lattice. The spin fluctuations of the nematic phase may be similar to the low-energy excitations of the striped phase. It is shown that the nematic phase may result in the anisotropy of the low-energy spin excitations in the cuprate YBCO [129]. The nematic phase may also exist in the Fe-based superconductors [130, 131]. However, we note that the anisotropic spin excitations in Fe-based superconductors can also be understood based on the Fermi surface nesting picture [132–134].

The hidden order in the heavy-fermion superconductor URu_2Si_2 has attracted a lot of attention. Figure 6(c) shows the electronic phase diagram of this material [135]. At low pressure, a large amount of entropy is released across T_0. The electronic state also shows features of condensation, indicating the formation of some kind of order. While neutron scattering experiments have demonstrated the presence of a static AF order below T_0, the small magnetic moment ($\sim 0.03\ \mu_B$) cannot explain the large loss of entropy found in specific heat measurements. This is also inconsistent with a large magnetic moment ($\sim 0.4\ \mu_B$) found at high pressures. A spin gap has been found in the spin excitations below T_0 [Fig. 6(d)] [136], whose energy change may explain the entropy change across T_0. A "resonance" peak is also found in the hidden ordered phase but absent in both the high-pressure AF phase and SC phase [137]. It is interesting to note that a type of "hidden" order and some "hidden" magnetic excitations that are related to the pseudogap are also found in cuprates [138, 139] but the origin of such order is different from that in URu_2Si_2.

4 Conclusions

While the establishment of BSC theory finished our search for the mechanism of the conventional

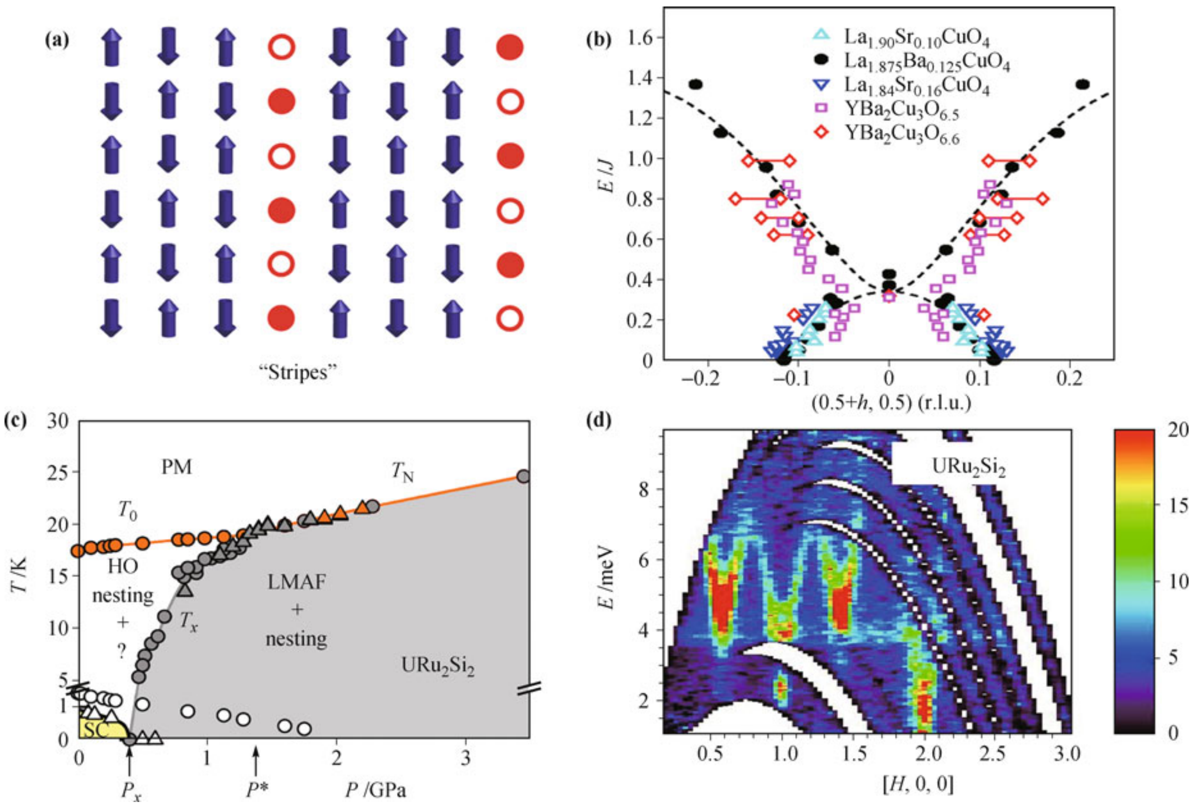

Fig. 6 **(a)** Schematic diagram of the stripes phase. The arrows represent the orientation of the magnetic moments. The filled circles denote holes in the CuO$_2$ planes. Note: the arrangement of the hollow and filled circles just suggests that the system is 1/8 hole doped. **(b)** Hourglass dispersion of the spin excitations in cuprates [125]. **(c)** Pressure phase diagram of the heavy fermion superconductor URu$_2$Si$_2$ [135]. **(d)** The spin excitations of URu$_2$Si$_2$ at 1.5 K (the hidden order phase) [136], where the dispersion at (2, 0, 0) comes from phonons.

superconductors, much is still not known for high-temeprature superconductors. For most unconventional superconductors, spin fluctuations seem to play important roles in determining their electronic properties. Experimentally, the spin dynamics in many materials have not been well studied due to the difficulty in growing high-quality large single crystals and the limitations of the neutron scattering technique. Theoretically, it is still unclear whether spin fluctuations may be treated as a "glue" to induce the pairing of two electrons. Only by systematically carrying out more neutron scattering experiments on different systems, one can hope to gradually determine the role of spin excitations for high-temperature superconductivity.

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