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Impurity and magnetic field effects on the stripes in cuprates

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ABSTRACT

Impurity and magnetic field effects on the stripes are reviewed not only in the La-based cuprates but also in the other high-T_c cuprates. It has turned out that the so-called 1/8 anomaly takes place not only in the La-based cuprates but also in the hole-doped high-T_c cuprates universally, when adequate pinning centers are introduced. Impurity-induced magnetism tends to emerge at low temperatures in a wide range of hole concentration in LSCO, Bi2201 and YBCO where superconductivity appears. Accordingly, it is possible that the dynamically fluctuating stripes exist universally in the hole-doped high-T_c cuprates and play an important role in the appearance of the high-T_c superconductivity. For the hole-doped high-T_c cuprates, it has turned out that magnetic field effects on the stripes are small in samples where the stripes are well stabilized statically in zero field, while field-induced magnetism is observed under magnetic fields parallel to the *c*-axis in underdoped samples where magnetism is not well developed in zero field. The field-induced magnetism has been observed in some optimally doped samples also, but it has never been observed in overdoped samples. Field-induced CDW has been observed in slightly overdoped BSCCO. These results are understood fundamentally in terms of the theoretical phase diagram as a function of magnetic field, based on the Ginzburg–Landau theory with competing antiferromagnetic and superconducting order parameters. It is also possible to understand that the field-induced magnetism and CDW are due to pinning of the dynamically fluctuating stripes by vortex cores as in the case of the pinning by impurities. In the electron-doped high-T_c cuprates, on the other hand, impurity-induced magnetism has never been observed. The nature of the field-induced magnetism observed in the electron-doped cuprates is different from that in the hole-doped ones.

1. Impurity effects

In general, impurities break the periodicity of the potential which electrons feel. Therefore, the dynamics of stripes of holes and spins in the high-T_c cuprates is guessed to be affected by impurities, as well as the dynamics of charge density wave (CDW) and spin density wave (SDW) in non-superconducting materials, for the stripes are a kind of CDW and SDW. Impurities, whose valences are different from those of constituent elements, are guessed to affect the state of the stripes, for this is dependent on the hole concentration. Impurity effects on the stripes in the high-T_c cuprates have markedly been observed in relation to the 1/8 anomaly, namely, the anomalous suppression of superconductivity at the hole concentration in the CuO_2 plane, $p \sim 1/8$ per Cu, because the 1/8 anomaly is caused by the static stabilization of the stripes. First, therefore, impurity effects on the 1/8 anomaly are described. Secondly, impurity effects on the stripes in a wide range of hole concentration and also in the electron-doped cuprates are discussed in relation to the stripes. Finally, the dependence of the impurity effects on the kind of impurity is described.

1.1. Impurity effects on the 1/8 anomaly

The 1/8 anomaly was first found in $La_{2-x}Ba_xCuO_4$ (LBCO) in 1988 just after the discovery of the high-T_c superconductivity [1,2]. The superconductivity is strongly suppressed at $x = p = 1/8$ in LBCO. In $La_{2-x}Sr_xCuO_4$ (LSCO), the superconductivity is a little suppressed about $x = 0.115$, which is a little different from 1/8, though the reason is not clear. The origin of the 1/8 anomaly was clarified to be due to a long-range magnetic order from the muon-spin-relaxation (μSR) experiment in LBCO [3] and LSCO [4], but the details of the order were unclear. In 1995, the details were clarified by Tranquada et al. [5] from the neutron scattering experiment using a large-sized single-crystal of $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ with $x = 0.12$ whose superconductivity was strongly suppressed. That is, it has been found that such a stripe order of holes and spins as shown in Fig. 1, namely, a combined state of CDW and SDW is realized in the CuO_2 plane, leading to the suppression of superconductivity.

From several experimental results of the impurity effects on the 1/8 anomaly, it has been found that the hole concentration, namely, $p = 1/8$ is essential for the appearance of the 1/8 anomaly. To describe it concretely, it has experimentally been revealed that the position of the dip in the superconducting (SC) transition

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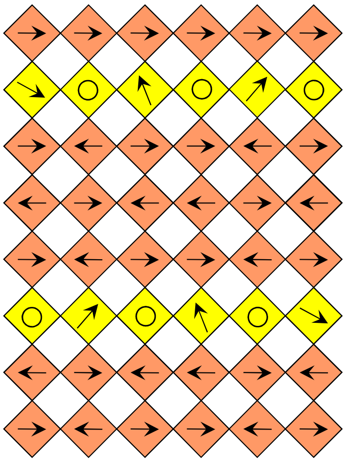

Fig. 1. Schematic picture of the stripe order of holes (circles) and spins (arrows) in the CuO_2 plane.

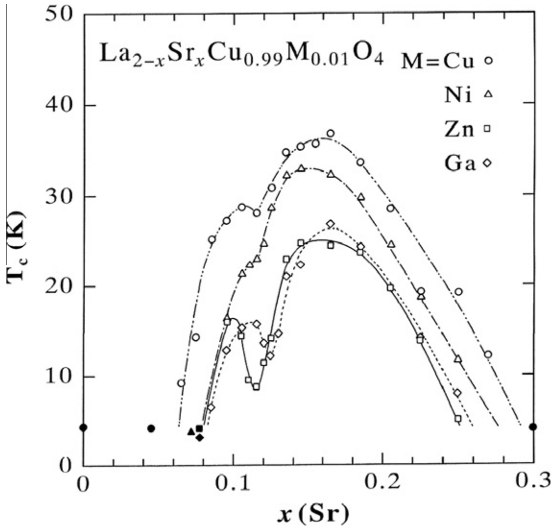

Fig. 2. Sr-concentration x dependence of T_c for non-substituted (circles), 1% Ni-substituted (triangles), 1% Zn-substituted (squares) and 1% Ga-substituted (diamonds) $La_{2-x}Sr_xCu_{0.99}M_{0.01}O_4$ (M = Cu, Ni, Zn, Ga) [9]. Closed symbols indicate samples whose T_c's are not above 4.2 K.

temperture, T_c, vs. x plot shifts from $x = 1/8$ to $x = 0.135$ in 1% Ga-substituted $La_{2-x}Ba_xCu_{0.99}Ga_{0.01}O_4$ [6] and from $x = 1/8$ to $x = 0.145$ in Ce-substituted $La_{1.98-x}Ce_{0.02}Ba_xCuO_4$ [7] and Th-substituted $La_{1.98-x}Th_{0.02}Ba_xCuO_4$ [8]. Since valences of the substituted Ga^{3+}, Ce^{4+} and Th^{4+} are larger than those of Cu^{2+}, La^{3+} and La^{3+}, respectively, the substitution gives rise to electron-doping into the CuO_2 plane. Therefore, the shift of the position of the dip in the T_c vs. x plot indicates that $p = 1/8$ is essential for the appearance of the 1/8 anomaly. A similar result was observed in 1% Ga-substituted $La_{2-x}Sr_xCu_{0.99}Ga_{0.01}O_4$ also, as shown in Fig. 2 [9].

The tetragonal low-temperature (TLT) structure (space group: $P4_2/ncm$) has been found to be more favorable for the appearance of the 1/8 anomaly, for the 1/8 anomaly is more marked in LBCO with the TLT structure than in LSCO without the TLT structure. In fact, when the TLT structure was suppressed through the partial substitution of Bi or Y for La in LBCO, the superconductivity was recovered [10,11]. When the TLT structure was induced through the partial substitution of rare-earth elements with small ionic-radii for La in LSCO, on the contrary, the superconductivity was suppressed, namely, the 1/8 anomaly was enhanced [12,13]. The preference of the TLT structure in the appearance of the 1/8 anomaly is reasonable, because the CuO_2 plane buckles, namely, the CuO_6 octahedra alternately rotate a little with the rotation axis parallel to the stripes so that the stripes are stabilized more easily in the TLT structure than in the others.

Since the stripes are a kind of CDW and SDW, it is expected that the stripes are statically stabilized due to the pinning of dynamically fluctuating stripes by impurities, leading to the enhancement of the 1/8 anomaly. As shown in Fig. 2, in fact, the 1/8 anomaly has been found to be enhanced through the 1% substitution of Zn or Ga for Cu in LSCO, though the 1% Ni-substitution is not effective for the enhancement of the 1/8 anomaly [9]. Moreover, it has been confirmed from the μSR experiment that the volume of the magnetically ordered region due to the static stripes increases through the Zn substitution around $x = 0.115$ in LSCO more markedly than through the Ni substitution [14–18]. Since the increase of the volume of the magnetically ordered region estimated from the μSR experiment is well corresponding to the decrease of the SC volume fraction estimated from the magnetic-susceptibility measurements, it has been concluded that the superconductivity is destroyed like Swiss cheese around Zn where the dynamically fluctuating stripes are pinned [16,17,19,20]. Theoretically, the static stabilization of the stripes through the Zn substitution was pointed out by the numerically exact diagonalization study of the t–J model [21]. Recently, the elastic neutron scattering experiment has revealed that the 1% substitution of Fe for Cu strikingly enhances the static stripes of holes as well as spins in LSCO [22].

Here, it is noted that the incommensurate magnetic peaks due to the static stripes observed in the elastic neutron-scattering experiment [5] is analogous to those observed in the inelastic neutron-scattering in a wide range of hole concentration in LSCO [23]. This suggests a scenario that dynamically fluctuating stripes exist in the CuO_2 plane of the high-T_c cuprates in a wide range of hole concentration and that the period of the stripes is well adjusted with the period of the CuO_2 plane at $p = 1/8$ so that the dynamically fluctuating stripes are pinned by the TLT structure or impurities to be statically stabilized around $p = 1/8$. If this is the case, it is possible that the dynamically fluctuating stripes play an important role in the appearance of the high-T_c superconductivity as theoretically proposed by Kivelson et al. [24]. Moreover, the 1/8 anomaly is expected to take place not only in the La-based high-T_c cuprates but also in the other high-T_c cuprates, when adequate pinning centers are introduced into a sample. In fact, the 1/8 anomaly was observed in 2.5% Zn-substituted Bi2212, namely, $Bi_2Sr_2Ca_{1-x}Y_x(Cu_{1-y}Zn_y)_2O_{8+\delta}$, as shown in Fig. 3 [25]. Furthermore, the μSR experiment has revealed that the depolarization rate of muon spins is anomalously enhanced at low temperatures at $p \sim 1/8$ in 2.5% Zn-substituted Bi2212 as shown in Fig. 3, though no clear precession of muon spins is observed [26,27]. A fast depolarization of polarized muon-spins injected into a sample in zero field is caused by static or slowly fluctuating internal fields due to electron spins at stopping sites of muons. In other words, the depolarization rate is so small when electron spins are fluctuating fast in a paramagnetic state, because muon spins feel no internal field due to the electron spins on average. Moreover, a precession of muon spins is observed when the internal fields are long-range-ordered. Therefore, this result indicates that the fluctuation of Cu^{2+} spins exhibits slowing down at $p \sim 1/8$ and suggests that the dynamically fluctuating stripes tend to be pinned by Zn at $p \sim 1/8$.

A similar μSR result was obtained in $YBa_2Cu_3O_{7-\delta}$ (YBCO) as well. That is, the depolarization rate of muon spins is anomalously enhanced at $7-\delta = 6.65$, namely, at $p \sim 1/8$ in partially Zn-substituted $YBa_2Cu_{3-2y}Zn_{2y}O_{7-\delta}$ with $y = 0.025$, as shown in Fig. 4, suggesting that the dynamically fluctuating stripes tend to be

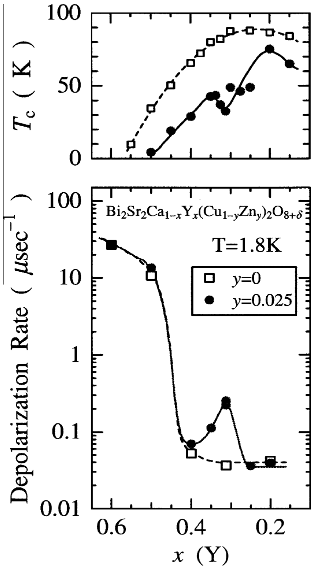

Fig. 3. Y-concentration x dependences of T_c and the depolarization rate of muon spins at 1.8 K in the μSR experiment for Zn-free (squares) and 2.5% Zn-substituted (circles) $Bi_2Sr_2Ca_{1-x}Y_x(Cu_{1-y}Zn_y)_2O_{8+\delta}$ [25–27]. The $x = 0.31$ is corresponding to the hole concentration in the CuO_2 plane, $p = 1/8$.

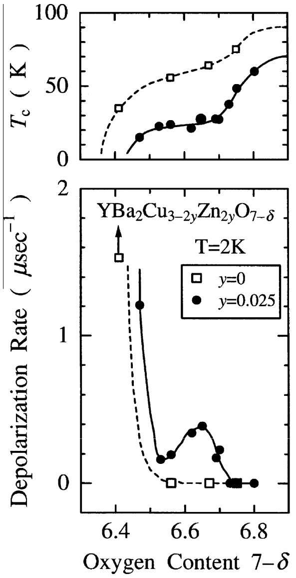

Fig. 4. Dependences on the oxygen content $7-\delta$ of T_c and the depolarization rate of muon spins at 2 K in the μSR experiment for Zn-free (squares) and Zn-substituted (circles) $YBa_2Cu_{3-2y}Zn_{2y}O_{7-\delta}$ with $y = 0$ and 0.025 [28]. The $7-\delta = 6.65$ is corresponding to the hole concentration in the CuO_2 plane, $p = 1/8$.

pinned by Zn at $p \sim 1/8$ [28]. Using detwinned single-crystals of $YBa_2(Cu_{0.98}Zn_{0.02})_3O_{6.6}$, recently, the above μSR result was reconfirmed, and moreover Zn-induced uniaxial incommensurate spin excitations were observed at low energies in the inelastic neutron-scattering experiment [29]. Accordingly, it is likely that the so-called 60 K-plateau in the T_c vs. $7-\delta$ plot in YBCO is due to the 1/8 anomaly [30–32]. As for the Zn-induced magnetism at $p \sim 1/8$ in YBCO, the existence of Zn-induced local moments was pointed out for the first time from ^{89}Y NMR in lightly Zn-substituted $YBa_2(Cu_{1-y}Zn_y)_3O_{6.64}$ with $p \sim 1/8$ [33]. The development of staggered moments, namely, the enhancement of antiferromagnetic (AF) correlation around Zn was indicated from ^{63}Cu NMR in $YBa_2(Cu_{0.99}Zn_{0.01})_3O_{6.7}$ with $p \sim 1/8$ [34]. In lightly Zn- or Ni-substituted underdoped $YBa_2(Cu_{1-x}M_x)_4O_8$ (M = Zn, Ni) as well, impurity-induced magnetism was observed in the Cu NQR experiment [35].

As for the 1/8 anomaly observed in the other high-T_c cuprates, it was observed in Nd-substituted excess-oxygen-doped $La_{1.8}Nd_{0.2}CuO_{4+\delta}$ where the phase separation of the excess oxygen was suppressed through the partial substitution of Nd for La [36,37], and furthermore a clear precession of muon spins due to the static stripes of spins was observed in 1% Zn-substituted $La_{1.8}Nd_{0.2}Cu_{0.99}Zn_{0.01}O_{4+\delta}$ with $\delta = 0.0625$, namely, $p = 1/8$ [36]. The 1/8 anomaly was observed in 0.5% Zn-substituted $Ca_{2-x}Na_xCu_{0.995}Zn_{0.005}O_2Cl_2$ as well, and a fast depolarization of muon spins due to the slowing down of the Cu-spin fluctuations was observed at $x = 1/8$ [38]. In conclusion, it has turned out that the 1/8 anomaly takes place universally in the hole-doped high-T_c cuprates, when adequate pinning centers such as Zn are introduced. Accordingly, it is possible that the dynamically fluctuating stripes exist universally in the hole-doped high-T_c cuprates and play an important role in the appearance of the high-T_c superconductivity.

1.2. Impurity effects on the stripes in a wide range of hole concentration and in the electron-doped cuprates

If the dynamically fluctuating stripes exist in a wide range of hole concentration and play an important role in the appearance of the high-T_c superconductivity, the pinning of the stripes by impurities should be observed in a wide range of hole concentration where superconductivity appears. From the theoretical point of view, the static stabilization of the stripes through the Zn substitution was pointed out by the numerically exact diagonalization study of the t–J model, as described above [21]. The reduction of T_c due to the pinning of the stripes by impurities was theoretically explained using a geometrical model [39]. Recent calculations of the dynamical spin susceptibility in the presence of nonmagnetic disorder in the underdoped high-T_c cuprates using an unrestricted Hartree-Fock approach have revealed that the Cu-spin fluctuations slow down around disorder and eventually freeze out, so that a disorder-induced SDW droplet phase becomes stable when the electronic repulsion, U, is small, while a disorder-induced stripe phase becomes stable when U is large [40].

In fact, Zn-induced slowing down of the Cu-spin fluctuations was observed at low temperatures in the μSR experiment in a wide range of hole concentration in $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$ ($0.10 \leq x < 0.30$) where superconductivity appears [16,20,41]. Fig. 5 shows the μSR time spectra, namely, the time evolutions of the depolarization of polarized muon-spins injected into $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$ in zero field at various temperatures. At high temperatures of 15–20 K, the depolarization is found to be slow, indicating that Cu^{2+} spins are fluctuating fast. At low temperatures, on the other hand, a fast depolarization is observed in Zn-free samples of $x = 0.10$ and 0.115 where the 1/8 anomaly is marked, indicating that the Cu-spin fluctuations exhibit slowing down. Through the light substitution of Zn, a precession of muon spins is observed for $x = 0.10$–0.13, though the damping is fast. This suggests that the dynamically fluctuating stripes are statically stabilized so that a static stripe order is realized. Moreover, a fast depolarization is observed in a wide range of hole concentration up to $x = 0.27$ where superconductivity appears. Since the Zn-induced slowing down of the Cu-spin fluctuations is able to be interpreted as being due to the pinning of the dynamically fluctuating stripes by Zn, these results suggest that the dynamically fluctuating stripes exist in a wide range of hole concentration. Here, it is noted that a small amount of Zn is not enough to pin the stripes in the overdoped regime where the Cu-spin fluctuations are large, while a large amount of Zn is also not good to

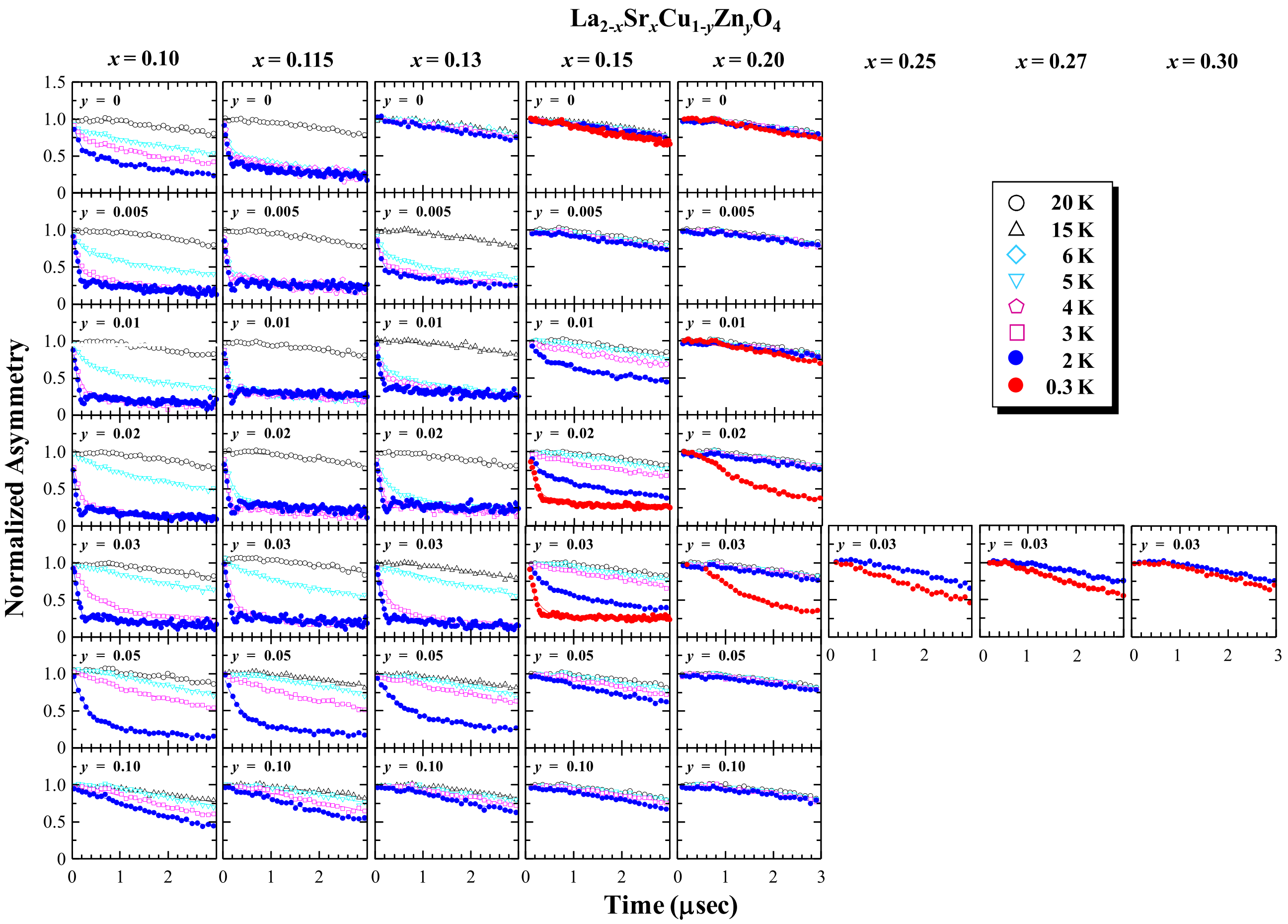

Fig. 5. μSR time spectra of $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$ ($0.10 \leqq x \leqq 0.30$; $0 \leqq y \leqq 0.10$) in zero field at various temperatures [16,20,41].

pin the stripes because of the dilution of Cu^{2+} spins by spinless Zn. Therefore, both low temperature and an adequate amount of Zn (about 3% Zn-substitution) are necessary to pin the stripes in the overdoped regime of LSCO. There were reports insisting that no fast depolarization was observed in the μSR experiment at $x \geqq 0.19$ in 1%, 2% and 5% Zn-substituted $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$ [42,43], but probably the amount of Zn was not suitable for the detection of the pinning of the stripes.

From the neutron scattering experiment, in fact, Zn-induced incommensurate magnetic peaks suggesting the static stabilization of the stripes and also Zn-induced incommensurate spin excitations with low energies, namely, the so-called in-gap states were observed in lightly Zn-substituted $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$ with $x = 0.14$ and 0.15 [44–46]. It may also be an evidence for the existence of the dynamically fluctuating stripes in a wide range of hole concentration in LSCO that the stripes are statically stabilized at $x = 0.08$–0.25 in Nd-substituted $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ with the TLT structure [47] and at $x = 0.08$–0.18 in Eu-substituted $La_{1.8-x}Eu_{0.2}Sr_xCuO_4$ with the TLT structure [48] and that the superconductivity at $x = 0.16$ in $La_{1.8-x}Eu_{0.2}Sr_xCuO_4$ is easily controlled by uniaxial pressure maybe adjusting the stability of the stripes [49]. According to the recent elastic neutron-scattering experiment, Fe-induced incommensurate magnetic peaks were observed in 1% Fe-substituted heavily overdoped $La_{2-x}Sr_xCu_{1-y}Fe_yO_4$ with $x = 0.25$ and 0.29, but they were concluded to be not due to the stripes but due to the Fermi surface nesting, combined with the angle-resolved photoemission study [50]. The recent μSR experiment has also revealed that the nature of the Fe-induced magnetism in overdoped LSCO is different from that in underdoped LSCO [51]. At present, the origin of the Fe-induced magnetism in overdoped LSCO is controversial. In addition, it is noted that an anomaly, which is associated with the 1/8 anomaly but small, is observed at $x \sim 0.21$ in LSCO. That is, a small dip is observed at $x \sim 0.21$ in the T_c vs. x plot and it is enhanced through the partial substitution of Zn, Ga and Fe for Cu [52–54]. This suggests that the dynamically fluctuating stripes may be statically stabilized singularly at $x \sim 0.21$ by some reason.

As for the impurity-induced magnetism in so-called Bi2201, a fast depolarization of muon spins due to the slowing down of the Cu-spin fluctuations was observed at low temperatures in the μSR experiment in a wide range of hole concentration in Zn-free $Bi_{1.74}Pb_{0.38}Sr_{1.88}CuO_{6+\delta}$ where superconductivity appears, and moreover the depolarization becomes faster in 3% Zn-substituted $Bi_{1.74}Pb_{0.38}Sr_{1.88}Cu_{0.97}Zn_{0.03}O_{6+\delta}$ than in Zn-free Bi2201, as shown in Fig. 6, suggesting that the dynamically fluctuating stripes exist in a wide range of hole concentration [55]. In the elastic neutron-scattering experiment of Fe-substituted overdoped $Bi_{1.75}Pb_{0.35}Sr_{1.90}Cu_{1-y}Fe_yO_{6+\delta}$, incommensurate magnetic peaks were observed, but the incommensurability was much larger than that in overdoped LSCO [56]. The Fe-induced magnetism is controversial in overdoped Bi2201 as well as in overdoped LSCO.

As for the Zn-induced magnetism in YBCO, a fast depolarization of muon spins due to the slowing down of the Cu-spin fluctuations was observed in the μSR experiment in 4% Zn-substituted underdoped $YBa_2(Cu_{0.96}Zn_{0.04})_3O_{7-\delta}$ with $7-\delta = 6.4$–6.7 [57]. In the inelastic neutron-scattering experiment of 2% Zn-substituted $YBa_2(Cu_{0.98}Zn_{0.02})_3O_{6.97}$, Zn-induced in-gap states were observed as in the case of LSCO [58].

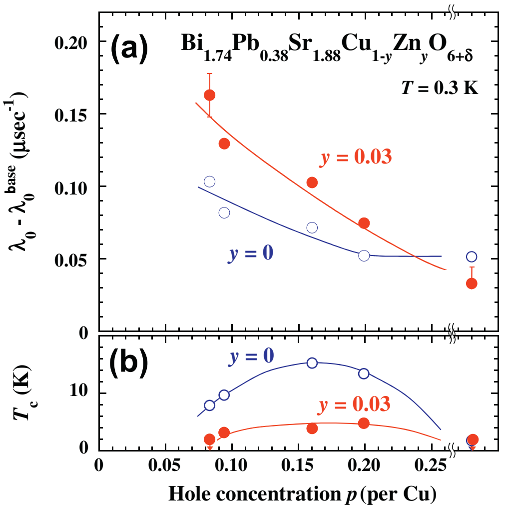

Fig. 6. Hole-concentration p dependences of (a) the depolarization rate of muon spins at 0.3 K in the μSR experiment and (b) T_c for Zn-free (open circles) and 3% Zn-substituted (closed circles) $Bi_{1.74}Pb_{0.38}Sr_{1.88}Cu_{1-y}Zn_yO_{6+\delta}$ [55].

In the electron-doped high-T_c cuprates, on the other hand, impurity-induced magnetism has never been observed [59]. The magnetic moments of constituent rare-earth ions in the electron-doped high-T_c cuprates may obscure a possible change of the Cu-spin fluctuations in the μSR experiment. Otherwise, the dynamically fluctuating stripes of electrons and spins may not exist, and the mechanism of the high-T_c superconductivity in the electron-doped cuprates may be different from that in the hole-doped cuprates.

1.3. Dependence of the impurity effects on the kind of impurity

As described above, the impurity effects on the stripes are denpendent on the kind of impurity. The effects of nonmagnetic Zn and Ga on the 1/8 anomaly were more marked than those of magnetic Ni in LBCO and LSCO [6,9]. In fact, the development of the static stripes detected by the μSR experiment was more marked in Zn-substituted LSCO than in Ni-substituted LSCO [17,20]. In the neutron scattering experiment, the in-gap state was developed in Zn-substituted LSCO, while it was not in Ni-substituted LSCO [46]. In lightly Zn- or Ni-substituted underdoped $YBa_2(Cu_{1-x}M_x)_4O_8$ (M = Zn, Ni), moreover, the Cu NQR experiment has revealed that the magnetically enhanced region around Zn is larger than around Ni [35]. These results are interpreted as follows. That is, nonmagnetic Zn^{2+} and Ga^{3+} disturb the Cu^{2+}-spin (with the spin quantum number $S = 1/2$) state in the CuO_2 plane more strongly than magnetic Ni^{2+} (with $S = 1$), so that both Zn^{2+} and Ga^{3+} pin the dynamically fluctuating stripes and destroy the superconductivity more markedly than Ni^{2+}. This scenario is also able to explain the unconventional result in the high-T_c cuprates that the superconductivity is destroyed by nonmagnetic impurities more markedly than by magnetic impurities [60]. According to recent experiments of neutron scattering [61,62], magnetic susceptibility [63], μSR [64], x-ray absorption fine structure [65], specific-heat [66,67] and a theoretical work using numerical exact diagonalization calculations [68], substituted Ni tends to trap a hole, forming a Zhang–Rice doublet state with the effective $S = 1/2$ similar to that of Cu^{2+}. This may be a reason why the effects of the Ni substitution are smaller than those of the Zn substitution. On the other hand, there is a report that the effects of the Zn and Ni substitution on the superconductivity and magnetism are not so different from each other in underdoped LSCO, taking into account the hole trapping by Ni [69].

As described above, the Fe substitution is much more effective for the stabilization of the stripes at $p \sim 1/8$ in LSCO than the Zn and Ga substitution [22,70]. It seems that a very large magnetic moment of Fe^{3+} with $S = 5/2$ strongly operates to pin the stripes. Even in the overdoped regime, only 1% Fe-substitution induces a magnetic order in LSCO [50,51] and also in Bi2201 [56], while the Zn substitution only slows down the Cu-spin fluctuations in LSCO [41] and in Bi2201 [55]. However, the magnetic order appears to be different from the simple stripe order. It may be due to the Fermi surface nesting or a new order created by large magnetic moments of Fe^{3+} ions on the background of weakly correlated Cu-spins.

2. Magnetic field effects

In general, the application of magnetic field suppressing superconductivity is effective for the investigation of the electronic ground state in the normal state hidden behind the superconductivity. The normal state inside vortex cores in a type-II superconductor induced by the application of magnetic field is also suggestive of the ground state. Besides, vortex cores operate to induce spatial inhomogeneity in a superconductor in some cases as well as impurities. Here, first, magnetic field effects on the 1/8 anomaly are described. Then, magnetic field effects on the stripes in a wide range of hole concentration and also in the electron-doped cuprates are discussed.

2.1. Magnetic field effects on the 1/8 anomaly

Magnetic field effects on the stripes were first investigated around $p = 1/8$ in LSCO. That is, in the elastic neutron-scattering experiment, a small enhancement of the incommensurate magnetic peaks due to the static stripes was observed by the application of magnetic field of 10 T parallel to the c-axis at $x = 0.12$ in LSCO [71]. Then, it has been found that the enhancement becomes marked at $x = 0.10$ [72] and that the field-induced magnetic order is three-dimensional (3D) [73]. In LBCO, on the other hand, the enhancement was small in a magnetic field of 10 T at $x = 0.10$ [74], and it was unobservable or very small at $x = 1/8$ [74,75]. At $x = 0.15$ in Nd-substituted $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ where the stripes were well stabilized statically in zero filed, neither magnetic peaks nor peaks due to the stripe order of holes were enhanced [76]. The μSR experiment in transverse field (TF) up to 6 T parallel to the c-axis has revealed that field-induced quasi-static magnetism exists even at high temperatures above T_c and above the magnetic transition temperature, T_N, at $x = 0.12$ in LSCO, at $x = 1/8$ in LBCO and at $x = 0.15$ in Eu-substituted $La_{1.9-x}Eu_{0.1}Sr_xCuO_4$ [77]. The x-ray scattering experiment at $x = 1/8$ in LBCO revealed an increase of the correlation length of the stripe order of holes by the application of magnetic field greater than ~5 T [78]. To summarize these results, magnetic field effects on the stripes are small in samples where the stripes are well stabilized statically in zero field such as LBCO with $x = 1/8$ and Nd-substituted $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ with $x = 0.15$, while the stripe order is developed by the application of magnetic field parallel to the c-axis in samples where it is not well developed in zero field such as LSCO. Moreover, even in samples where the stripes are well stabilized statically in zero field at low temperatures, the stripe order tends to be developed by the application of magnetic field at high temperatures above T_c and T_N where the stripes are not stabilized in zero field so much.

In fact, the above results were supported by the thermal conductivity measurements under magnetic field in LSCO [79]. That is, as shown in Fig. 7, the in-plane thermal conductivity is suppressed at low temperatures below the temperature T_κ, which is located a little above T_c, by the application of magnetic field

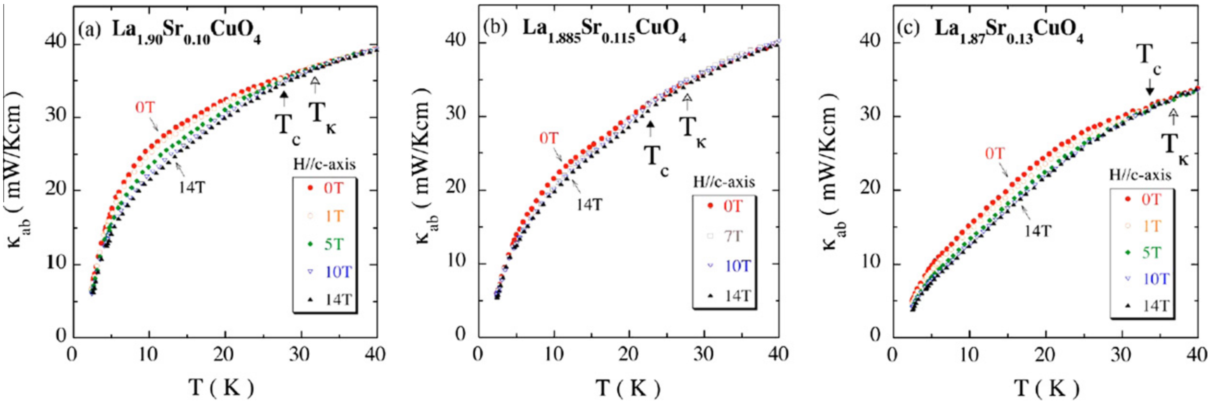

Fig. 7. Temperature dependence of the in-plane thermal conductivity of $La_{2-x}Sr_xCuO_4$ with $x = 0.10$, 0.115, 0.13 in magnetic fields parallel to the c-axis [79]. Closed and open arrows denote T_c and the temperature T_κ below which the in-plane thermal conductivity is suppressed by the application of magnetic field, respectively.

parallel to the c-axis. The suppression by the application of magnetic field is marked at $x = 0.10$ and 0.13, while it is small at $x = 0.115$ where the stripes are most stabilized in zero field in LSCO. Moreover, no suppression was observed at $x = 0.115$ in 1% Zn-substituted $La_{2-x}Sr_xCu_{0.99}Zn_{0.01}O_4$ where the stripes were well stabilized in zero field. The suppression at $x = 0.13$ was larger in 1% Ni-substituted $La_{2-x}Sr_xCu_{0.99}Ni_{0.01}O_4$ than in 1% Zn-substituted $La_{2-x}Sr_xCu_{0.99}Zn_{0.01}O_4$ where the stripes were more stabilized in zero field [80]. In LBCO, the suppression was more marked at $x = 0.10$ than at $x = 0.11$ where the stripes were more stabilized in zero field [81]. Supposing that the suppression of the in-plane thermal conductivity is due to the static stabilization of the stripes, these results are well corresponding to the above results in the neutron scattering and μSR experiments. Furthermore, it has been found from the thermal conductivity measurements that T_κ is almost independent of the magnitude of magnetic field and that the suppression is very small by the application of magnetic field perpendicular to the c-axis [79]. Therefore, these results strongly suggest that the field-induced magnetic order is due to pinning of the dynamically fluctuating stripes by vortex cores, because it is likely that vortex cores operate to induce spatial inhomogeneity in a superconductor to pin something. Theoretically, the field-induced magnetic order was explained by Demler et al. [82] as being due to a quantum phase transition from a pure SC phase to a coexisting phase of superconductivity and SDW and finally to a SDW phase as shown in Fig. 8, for the stripe order of spins is regarded as SDW.

The state of holes in the stripes was investigated by the in-plane electrical resistivity under magnetic field as well. That is, as shown in Fig. 9, the SC transition curve in the in-plane resistivity vs. temperature plot under magnetic field changes in parallel with increasing magnetic field in well stripe-ordered samples such as LBCO with $x = 0.11$ and $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ with $x = 0.12$ and 0.15, indicating that the superconductivity coexisting with the static stripe order is 3D with small SC fluctuations [76,83]. In usual underdoped samples such as LBCO with $x = 0.08$ shown in Fig. 9, on the other hand, the SC transition curve is well known to exhibit fan-shaped broadening with increasing field, indicating that the superconductivity is two-dimensional (2D) with large SC fluctuations [83]. Intriguing is that, as shown in Fig. 9, the SC transition curve changes from fan-shaped broadening to parallel shift with increasing field in LBCO with $x = 0.10$ and LSCO with $x = 0.115$, suggesting that the stripes are stabilized with increasing field [83–85]. Moreover, it has been found that the normal-state in-plane resistivity increases with increasing field in LBCO with $x = 0.10$ and LSCO with $x = 0.115$ as the stripes change to be stabilized, while it does not change in well stripe-ordered LBCO with $x = 0.11$ and 2% Zn-substituted $La_{2-x}Sr_xCu_{0.98}Zn_{0.02}O_4$ with $x = 0.115$ [85]. The increase of the normal-state in-plane resistivity with increasing field is interpreted as being due to the localization effect of holes confined in the stripes. Thus, the change of the stripes of holes with increasing field is investigated by the in-plane resistivity also. Besides, taking into account the result that the insulating behavior of the normal-state in-plane resistivity at low temperatures under magnetic field in underdoped LSCO is very similar to that in zero field in 2% Zn-substituted $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$, the role of magnetic field in the localization of holes appears to be the same as that of Zn [86]. Moreover, taking into account the result that the localization temperature is almost coincident with the set-in temperature of the slowing down of the Cu-spin fluctuations detected by the μSR experiment [87], the scenario seems reasonable that both magnetic field and impurities such as Zn operate to confine holes in the stripes, namely, pin the dynamically fluctuating stripes [85].

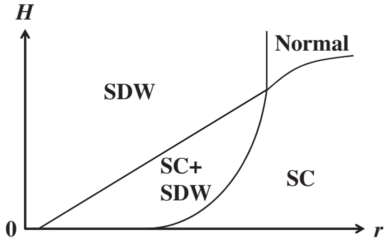

Fig. 8. Schematic phase diagram as a function of magnetic field and the parameter r, which is similar but not identical to the hole concentration, proposed by Demler et al. [82]. The SC denotes superconductivity.

2.2. *Magnetic field effects on the stripes in a wide range of hole concentration and in the electron-doped cuprates*

Magnetic field affects the electronic ground state in a system where some order is competing with superconductivity. The competing order is expected to appear in the core of a vortex. A general Ginzburg–Landau theory with competing AF and SC order parameters obtained from the SO(5) theory predicted that a SC vortex in underdoped high-T_c cuprates could have an AF core [88,89]. The development of the AF correlation inside vortex cores was predicted from the 2D t–J model using the Gutzwiller approximation as well [90]. On the other hand, a Bogoliubov-de Gennes theory based on the 2D Hubbard model indicated that there were no eminent low-energy electronic states even near vortex cores [91]. In the scanning tunneling microscopy (STM)/scanning tunneling spectroscopy (STS) experiment, in fact, localized electron states

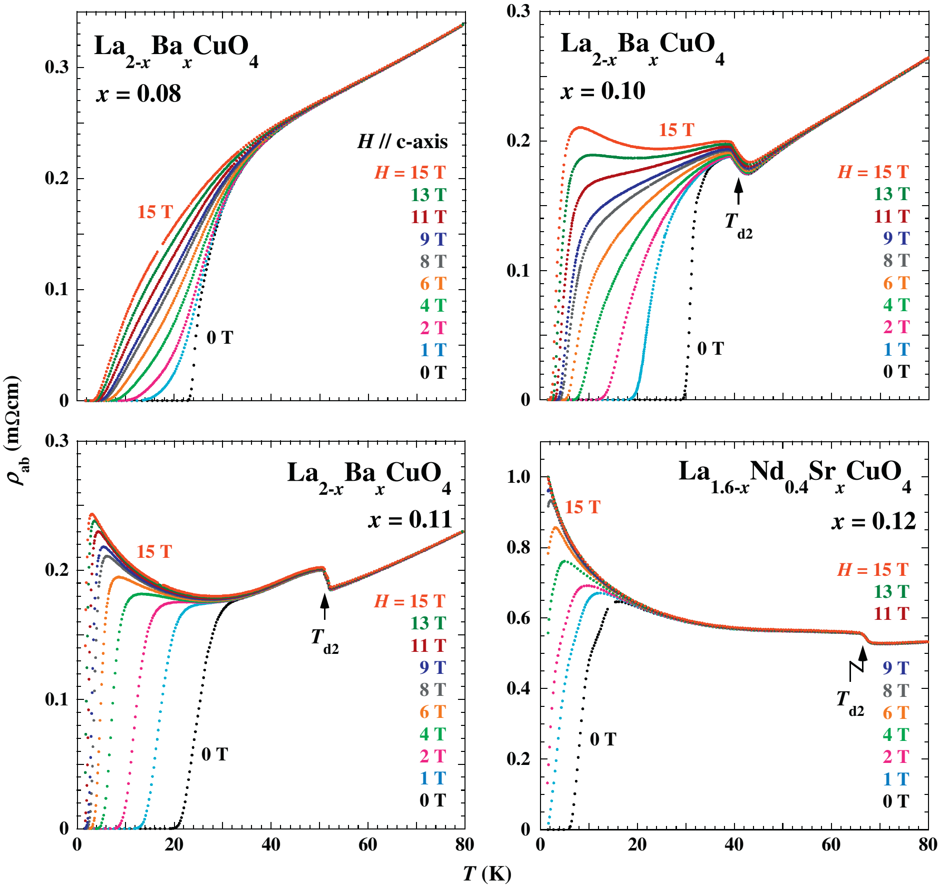

Fig. 9. Temperature dependence of the in-plane electrical resistivity, ρ_{ab}, in various magnetic fields parallel to the c-axis for $La_{2-x}Ba_xCuO_4$ with $x = 0.08$, 0.10, 0.11 and $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ with $x = 0.12$ [83]. The temperature where a jump of ρ_{ab} occurs is in correspondence to the structural phase transition temperature to the TLT or orthorhombic low-temperature phase, T_{d2}.

were observed in vortex cores in YBCO [92] and $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) [93,94]. From the NMR experiment, moreover, an AF order was suggested to be developed inside vortex cores in nearly optimally doped YBCO [95] and $Tl_2Ba_2CuO_{6+\delta}$ [96].

Based on the Ginzburg–Landau theory, a phase diagram as a function of magnetic field and the parameter r similar but not identical to the hole concentration was proposed by Demler et al. [82]. As shown in Fig. 8, a coexisting phase of superconductivity and SDW appears in some region and SDW is stabilized with increasing field, owing to the overlap of 2D vortices with low-energy spin fluctuations. This theory was applied to explain the field-induced stripe order around $p = 1/8$ as described in 2.1. According to the calculations taking into account fluctuation effects on the phase transitions in Fig. 8, it was proposed that a competing order could be stabilized about a nearly isolated 3D vortex and the phase diagram was a little modified [97]. As for the "normal" state in Fig. 8, a CDW order was predicted to appear there [98].

Apart from high-T_c cuprates relating to the 1/8 anomaly, experimentally, the coexisting phase of superconductivity and SDW was found at low temperatures in excess-oxygen-doped $La_2CuO_{4+\delta}$ with the stage-4 ($p \sim 0.14$) and stage-6 ($p \sim 0.06$) structures, and the development of SDW with increasing magnetic field was observed in the elastic neutron-scattering experiment [99,100]. The development of SDW was also observed with increasing field above ~3 T at $x = 0.144$ in LSCO in the elastic neutron-scattering experiment [101]. The so-called in-gap states were observed by the application of magnetic field of 7.5 T at $x = 0.163$ in LSCO in the inelastic neutron-scattering experiment [102]. The μSR experiment revealed spin-glass-like magnetism induced about vortex cores by the application of magnetic field at $x = 0.145$ in LSCO, while no field-induced magnetism was observed in overdoped LSCO with $x = 0.176$ [103] nor with $x = 0.19$ [77]. Regarding overdoped LSCO as being located in the large-r region of the theoretically proposed phase diagram shown in Fig. 8, these results are understood in terms of the phase diagram.

As for magnetic field effects in the other high-T_c cuprates, the neutron scattering experiment in underdoped YBCO with $7-\delta = 6.45$ has revealed that incommensurate magnetic peaks due to a static magnetic order are enhanced and the spectral weight at low energies is transferred to the elastic-scattering component with increasing magnetic field up to 15 T [104]. The μSR experiment revealed spin-glass-like magnetism induced about vortex cores by the application of magnetic field in underdoped YBCO with $7-\delta = 6.50$ as well as at $x = 0.145$ in LSCO, but did not in YBCO with $7-\delta = 6.60$ [103]. In optimally doped $Ca_{2-x}Na_xCuO_2Cl_2$, field-induced magnetism was observed even above T_c in the TF-μSR experiment [105]. On the other hand, no field-induced magnetism was observed in optimally doped $(Bi,Pb)_2Sr_2CaCu_2O_8$ nor 0.7% Zn-substituted $YBa_2(Cu_{0.993}Zn_{0.007})_3O_7$ in the TF-μSR experiment [77]. The STM/STS experiment in slightly overdoped BSCCO revealed a checkerboard pattern of the electronic modulation of the local density of states with a period of $\sim 4a_0$ in the regions surrounding the vortex core [106–108]. Since this CDW order had some degree of one-dimensionality, this might be relevant to the stripe order. These results are also understood in terms of the theoretically proposed phase diagram. In addition, since both LBCO and LSCO with $p \sim 1/8$ are regarded as being located in the small-r region in Fig. 8, the phase diagram is fundamentally able to explain the magnetic field effects on the electronic ground state in a wide range of hole concentration [109]. As described above, it is also possible to understand that vortices operate to pin the dynamically fluctuating stripes in underdoped high-T_c cuprates as well as impurities, leading to the development of the static stripe order, while the pinning of the stripes by vortices is not enough to develop the static stripe order in overdoped high-T_c cuprates as well as the pinning by impurities.

Here, it is noted that the TF-μSR experiment in overdoped LSCO has recently revealed a large broadening of the local magnetic field distribution in response to applied magnetic field [110]. The field response is approximately Curie-Weiss-like in temperature and increases with increasing x up to 0.30. These results are interpreted as being due to dopant-induced staggered magnetization seeded by Sr^{2+} disorder and stabilized by magnetic field. It attracts interest the relation to the magnetic order induced by the 1% substitution of Fe^{3+} with a very large magnetic moment in overdoped LSCO [50,51] and Bi2201 [56] as described in 1.3.

As for the anomaly at $x \sim 0.21$ in LSCO as described in 1.2 [52–54], anomalous magnetic field effects were observed in the ultrasonic velocity [111], thermal conductivity [112] and electrical resistivity [113] singularly at $x \sim 0.21$. The in-plane electrical resistivity under magnetic field at $x \sim 0.21$ has revealed that the SC transition curve changes from fan-shaped broadening to parallel shift with increasing field as in the case of LBCO with $x = 0.10$ and LSCO with $x = 0.115$ [113]. Therefore, the dynamically fluctuating stripes may tend to be stabilized by the application of magnetic field at x $\sim$ 0.21 as well as about $x = 1/8$.

In the electron-doped high-T_c cuprates, an enhancement of the commensurate magnetic peaks due to the AF order was observed in the elastic neutron-scattering experiment at $x = 0.11$ in $Pr_{1-x}LaCe_xCuO_4$ (PLCCO) and not at $x = 0.15$ [114]. Since $x = 0.11$ is located in the boundary region between AF and SC phases where both AF and SC islands coexist and moreover T_N does not change by the application of magnetic field, it has been speculated that the enhancement of the AF order by the application of magnetic field is not due to the vortex-induced magnetism but due to the simple reduction of SC islands and that the competitive coupling between the AF order and superconductivity is much weaker in the electron-doped cuprates than in the hole-doped ones. The field-induced magnetism was observed in the elastic neutron-scattering experiment at $x = 0.12$ in PLCCO as well [115]. It was also observed in the μSR experiment at $x = 0.11$ in PLCCO [116] and in SC $Pr_{2-x}Ce_xCuO_4$ [117].

3. Conclusions

It has turned out that the 1/8 anomaly takes place not only in the La-based cuprates but also in the hole-doped high-T_c cuprates universally, when adequate pinning centers such as Zn impurities are introduced. Moreover, impurity-induced magnetism tends to emerge at low temperatures in a wide range of hole concentration in LSCO, Bi2201 and YBCO where superconductivity appears. Accordingly, it is possible that the dynamically fluctuating stripes exist universally in the hole-doped high-T_c cuprates and play an important role in the appearance of the high-T_c superconductivity. In the electron-doped high-T_c cuprates, on the other hand, impurity-induced magnetism has never been observed. The origin of the Fe-induced magnetism in overdoped LSCO and Bi2201 is controversial at present.

For the hole-doped high-T_c cuprates, it has turned out that magnetic field effects on the stripe order are small in samples where the stripes are well stabilized statically in zero field, while field-induced magnetism is observed under magnetic fields parallel to the c-axis in underdoped samples where magnetism is not well developed in zero field. The field-induced magnetism has been observed in some optimally doped samples also, but it has never been observed in overdoped samples. Field-induced CDW has been observed in slightly overdoped BSCCO. These results are understood fundamentally in terms of the theoretical phase diagram as a function of magnetic field and the parameter r similar but not identical to the hole concentration, based on the Ginzburg–Landau theory with competing AF and SC order parameters. Since the role of magnetic field appears to be the same as that of impurities, it is also possible to understand that the field-induced magnetism and CDW are due to pinning of the dynamically fluctuating stripes by vortex cores. The field-induced magnetism has been observed in the electron-doped high-T_c cuprates also, but it does not appear due to the vortex-induced magnetism and the competitive coupling between the AF order and superconductivity appears much weaker in the electron-doped cuprates than in the hole-doped ones. At present, the origin of the large broadening of the local magnetic field distribution in response to applied magnetic field in overdoped LSCO is not clear. Neither is the origin of the anomaly at $x \sim 0.21$ in LSCO, though the magnetic field effects on the anomaly are analogous to those on the 1/8 anomaly.

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