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Impurity Effects on the Stripes in the La-214, Bi-2212 and Y-123 Phases

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Abstract. Our recent experimental studies on the 1/8 anomaly in the Bi-2212 and Y-123 phases and on the new anomaly at $x = 0.21$ in $\text{La}_{2-x}\text{Sr}_x\text{Cu}_{1-y}\text{Zn}_y\text{O}_4$ are reviewed. In the Zn-substituted Bi-2212 and Y-123 phases, we have found anomalous suppression of superconductivity at p (the hole concentration per Cu in the CuO_2 plane) $\sim 1/8$, and it has been found from the muon spin relaxation (μ SR) measurements that the magnetic correlation between Cu spins is enhanced singularly at $p \sim 1/8$. Furthermore, we have found marked suppression of superconductivity singularly at $x = 0.21$ in the 1% Zn-substituted single-crystals of $\text{La}_{2-x}\text{Sr}_x\text{Cu}_{1-y}\text{Zn}_y\text{O}_4$, and it has been found from the μ SR measurements that the magnetic correlation is also enhanced at $x = 0.21$. These results suggest that the dynamical stripe correlations of holes and spins exist in the Bi-2212 and Y-123 phases as well as in the La-214 phase and that they tend to be pinned by Zn, leading to the suppression of superconductivity. If this tendency is the case in a wide range of p , it is possible to understand the universal results in the high- T_c cuprates that Zn is a strong scatterer and that the Zn substitution markedly suppresses superconductivity.

INTRODUCTION

Recently, it has been pointed out from the inelastic neutron-scattering experiments that stripe correlations of holes and spins exist in a wide range of hole concentration in the La-214 phase [1] and also in the Bi-2212 [2] and Y-123 [3, 4] phases. The stripe correlations have attracted great interest in relation to the mechanism of the high- T_c superconductivity (SC). However, when the dynamical stripe correlations are pinned to become a static stripe-order at p (the hole concentration per Cu in the CuO_2 plane) $\sim 1/8$ in the La-214 phase, the SC is markedly suppressed [5]. This is called the 1/8 anomaly. Accordingly, the 1/8 anomaly is expected to appear in the other high- T_c cuprates, when adequate pinning centers are introduced into a sample. In fact, we have found the 1/8 anomaly in the Bi-2212 [6-9] and Y-123 [9-11] phases by introducing a small amount of Zn into a sample. Moreover, we have found a new anomaly at $x = 0.21$ in the overdoped region of $\text{La}_{2-x}\text{Sr}_x\text{Cu}_{1-y}\text{Zn}_y\text{O}_4$, which suggests the existence of a static stripe-order as well as at $x = 0.115$ [12-15].

In this paper, we review our experimental studies from the transport and μ SR measurements on the 1/8 anomaly of the Bi-2212 and Y-123 phases and on the new anomaly at $x = 0.21$ in $\text{La}_{2-x}\text{Sr}_x\text{Cu}_{1-y}\text{Zn}_y\text{O}_4$.

EXPERIMENTAL

Sintered samples of $\text{Bi}_2\text{Sr}_2\text{Ca}_{1-x}\text{Y}_x(\text{Cu}_{1-y}\text{M}_y)_2\text{O}_{8+\delta}$ ($M = \text{Zn}, \text{Ni}$) of the Bi-2212 phase and those of $\text{Y}_{1-x}\text{Ca}_x\text{Ba}_2\text{Cu}_{3-2y}\text{Zn}_{2y}\text{O}_{7-\delta}$ of the Y-123 phase were prepared by the solid-state reaction method. Single crystals of $\text{La}_{2-x}\text{Sr}_x\text{Cu}_{1-y}\text{Zn}_y\text{O}_4$ were grown by the TSFZ method. T_c was determined from the resistivity and magnetic susceptibility measurements. μ SR measurements were carried out at the RIKEN-RAL Muon Facility in the UK and at the KEK-MSL in Japan, using a spin-polarized pulsed surface muon beam with a momentum of 27 MeV/c.

RESULTS AND DISCUSSION

1/8 Anomaly in the Bi-2212 Phase

In order to pin the possible dynamical stripe correlations, Zn or Ni was partially substituted for Cu. As shown in Fig. 1, anomalous suppression of SC has been found at $x = 0.30 - 0.35$, where $p \sim 1/8$, in the Zn-substituted $\text{Bi}_2\text{Sr}_2\text{Ca}_{1-x}\text{Y}_x(\text{Cu}_{1-y}\text{Zn}_y)_2\text{O}_{8+\delta}$ with $y = 0.02 - 0.03$ [6]. In these samples, transport properties are also anomalous [6, 9]. Recently, our results have been confirmed by Ilonca and co-workers [16].

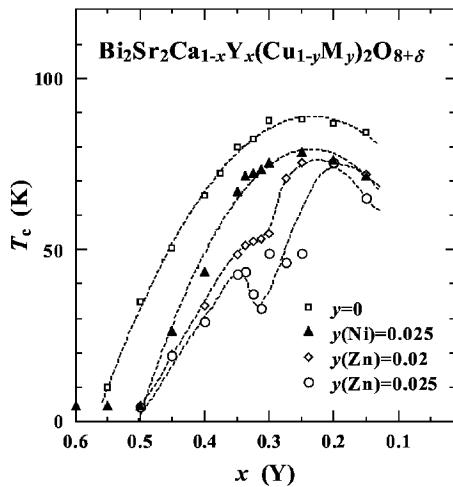


FIGURE 1. x dependence of T_c in $\text{Bi}_2\text{Sr}_2\text{Ca}_{1-x}\text{Y}_x(\text{Cu}_{1-y}\text{M}_y)_2\text{O}_{8+\delta}$ ($M = \text{Zn}, \text{Ni}$).

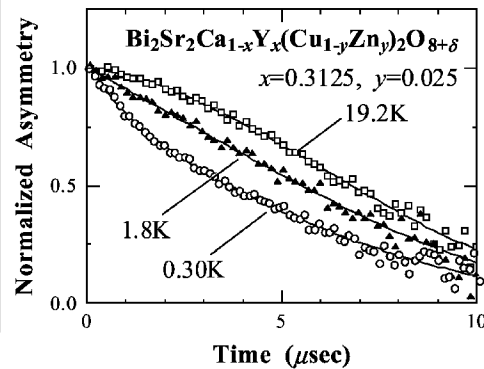


FIGURE 2. μ SR time spectra of $\text{Bi}_2\text{Sr}_2\text{Ca}_{1-x}\text{Y}_x(\text{Cu}_{1-y}\text{Zn}_y)_2\text{O}_{8+\delta}$ with $x = 0.3125$ and $y = 0.025$.

Fig. 2 shows μ SR time spectra of the Zn-substituted sample with $x = 0.3125$ and $y = 0.025$ [7, 8]. The depolarization behavior is of a Gaussian-type at high temperatures, indicating that the muon spins depolarize by only the nuclear dipole field. It changes to an exponential-type at low temperatures, while it is still of a Gaussian-type at low temperatures for the non-Zn-substituted sample with $x = 0.3125$ and $y = 0$. This suggests that the magnetic correlation between Cu spins is enhanced at low temperatures for the Zn-substituted sample so that the Cu-spin fluctuations slow down. On the other hand, it is well known that antiferromagnetic (AF) order appears in the underdoped region of the high- T_c cuprates. In fact, an increase of the muon-spin depolarization rate λ affected by the AF order has been observed in both the Zn-substituted and non-substituted samples with $x > 0.5$ in the underdoped region. As shown in Fig. 3, however, the increase of λ at $x = 0.3125$ in $y = 0.025$ is singular.

In order to investigate the magnetic state of Cu spins, longitudinal field (LF) was applied in the direction of the initial muon-spin polarization [17]. The time spectrum of the Zn-substituted sample with $x = 0.3125$ and $y = 0.025$ at 0.30 K has been found to exhibit a long-time depolarization behavior even in LF of 3950 G. This means that the Cu spins are still dynamically fluctuating even at 0.30 K, though the Cu-spin fluctuations slow down to some extent. The value of λ has been found to decrease with increasing LF with a square-root field dependence, suggesting the existence of one-dimensional (1D) diffusion of a magnetically excited state of the Cu spins [18]. Therefore, this LF dependence supports the existence of the 1D stripe-correlations in the Bi-2212 phase.

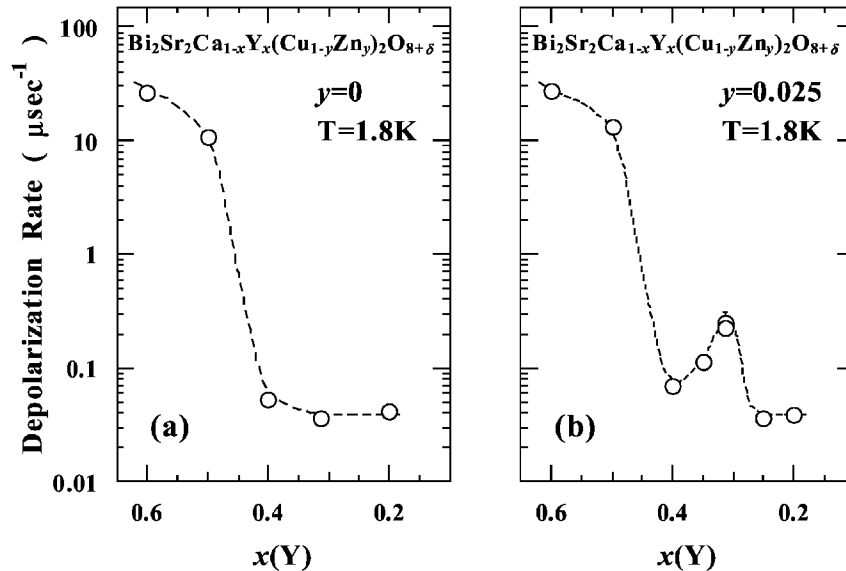


FIGURE 3. x dependence of the muon-spin depolarization rate at 1.8 K for (a) $y = 0$ and (b) $y = 0.025$ in $\text{Bi}_2\text{Sr}_2\text{Ca}_{1-x}\text{Y}_x(\text{Cu}_{1-y}\text{Zn}_y)_2\text{O}_{8+\delta}$.

As shown in Fig. 1, the Ni substitution is not effective for the suppression of SC at $p \sim 1/8$ in the Bi-2212 phase as in the case of the La-214 phase [19]. This would be reasonable, supposing that Zn^{2+} with the spin $S = 0$ pins the hole-rich domain in the stripe order more effectively than Ni^{2+} with $S = 1$. If this is the case, Zn will effectively scatter holes in the 1D path of the hole-rich domain and markedly decreases T_c . Furthermore, if this tendency is the case in a wide range of p , it is possible to understand the universal results in the high- T_c cuprates that Zn is a strong scatterer in the unitarity limit and that the Zn substitution decreases T_c more markedly than the Ni substitution. Accordingly, the above supposition does not seem irrelevant.

In the long run, it is concluded that there is a possibility that the dynamical stripe correlations tend to be pinned by a small amount of Zn at $p \sim 1/8$ in the Bi-2212 phase also, leading to the enhancement of the magnetic correlation and the suppression of SC.

1/8 Anomaly in the Y-123 Phase

In the Y-123 phase, the so-called 60-K plateau of T_c was known as being due to the ordering of oxygen atoms in the $CuO_{1-\delta}$ chain. We have investigated dependences of T_c in $Y_{1-x}Ca_xBa_2Cu_3O_{7-\delta}$ ($x = 0, 0.2$) on both the oxygen content $7-\delta$ and p [10]. Consequently, it has been found that the 60-K plateau is not correlated with $7-\delta$ but is correlated with p . Therefore, it has been concluded that the appearance of the 60-K plateau is interpreted as being due to the suppression of SC at $p \sim 1/8$ rather than the ordering of the oxygen atoms.

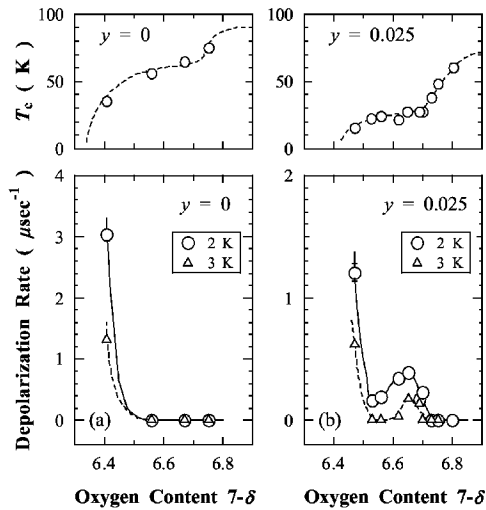


FIGURE 4. Oxygen-content dependences of T_c and the muon-spin depolarization rate at 2 and 3 K for (a) $y = 0$ and (b) $y = 0.025$ in $YBa_2Cu_{3-2y}Zn_{2y}O_{7-\delta}$.

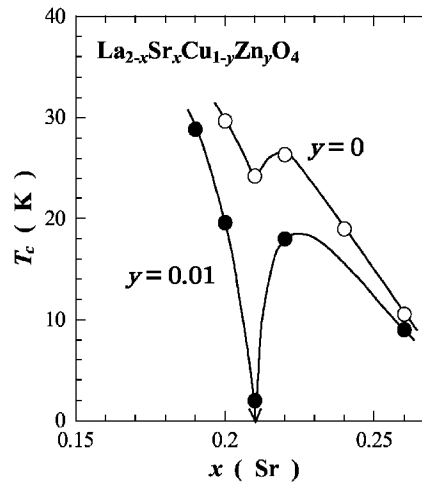


FIGURE 5. x dependence of T_c in the single-crystal $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$ with $y = 0$ and 0.01 .

The μ SR time spectrum of the Zn-substituted $\text{YBa}_2\text{Cu}_{3-2y}\text{Zn}_{2y}\text{O}_{7-\delta}$ with $7-\delta = 6.65$ and $y = 0.025$, where $p \sim 1/8$, has been found to change from a Gaussian-type to an exponential-type at low temperatures, while it is still of a Gaussian-type for the non-substituted sample with $p \sim 1/8$ [9]. This suggests that the magnetic correlation between Cu spins is enhanced at low temperatures for the Zn-substituted sample. As in the case of the Bi-2212 phase, λ is enhanced in the underdoped region, owing to the influence of the AF order. As shown in Fig. 4, however, the increase in λ in the Zn-substituted sample with $7-\delta = 6.65$ is singular [11]. In the former μ SR measurements of the heavily Zn-substituted samples of the Y-123 phase, no slowing-down behavior was reported at $p \sim 1/8$ [20]. This suggests that a large amount of Zn operates to destroy the magnetic correlation. Therefore, it is concluded that there is a possibility that the dynamical stripe correlations tend to be pinned by a small amount of Zn at $p \sim 1/8$ in the Y-123 phase as well as in the Bi-2212 phase, leading to the enhancement of the magnetic correlation and the suppression of SC.

New Anomaly at $x = 0.21$ in the La-214 Phase

Although we have already found a new anomaly in the overdoped region of $\text{La}_{2-x}\text{Sr}_x\text{Cu}_{1-y}\text{Zn}_y\text{O}_4$ [12, 13], we have recently confirmed it using single crystals of good quality [14]. Fig. 5 displays the x dependence of T_c in the 1% Zn-substituted and non-Zn-substituted single-crystals. It is found that the SC is markedly suppressed at $x = 0.21$ in the 1% Zn-substituted single-crystals and that it is a little suppressed at $x = 0.21$ in the non-Zn-substituted ones. In the 1% Zn-substituted crystal with $x = 0.21$, the electrical resistivity exhibits upturn at low temperatures below ~ 80 K and the temperature dependence of the thermoelectric power is also anomalous. From the μ SR measurements, it has been found that the magnetic correlation is enhanced at low temperatures below 3.5 K in the 1% Zn-substituted crystal with $x = 0.21$, while it is enhanced below 0.8 K in the non-Zn-substituted crystal with $x = 0.21$ [15]. Moreover, incommensurate magnetic peaks around (π, π) have been observed by Kimura *et al.* [21] from the elastic neutron-scattering experiment, which is similar to those observed from the inelastic neutron-scattering experiment in the overdoped region. These results strongly suggest that the dynamical stripe correlations of holes and spins tend to become static at $x = 0.21$ and are pinned by Zn, leading to a static stripe-order and the marked suppression of SC, as in the case of $x = 0.115$ [19].

CONCLUSIONS

The $1/8$ anomaly has been found not only in the La-214 phase but also in the Bi-2212 and Y-123 phases. Furthermore, a new anomaly has been found at $x = 0.21$ in the La-214 phase. In conclusion, it is very likely that the dynamical stripe correlations of holes and spins exist in all high- T_c cuprates and that they tend to be pinned by a small amount of Zn at $p \sim 1/8$ and also at $x = 0.21$ in the La-214 phase, leading to the enhancement of the magnetic correlation and the suppression of SC. If this tendency is the case in a wide range of p , it is possible to understand the universal results in the high- T_c cuprates that Zn is a strong scatterer in the unitarity limit and that the Zn

substitution markedly suppresses SC. Finally, it may be pointed out that the dynamical stripe correlations of hole and spins may play an important role in the appearance of high- T_c SC, while the static stripe-order are not favorable for SC.

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