Complementary Response of Static Spin-Stripe Order and Superconductivity to Nonmagnetic Impurities in Cuprates
Z. Guguchia, B. Roessli, R. Khasanov, A. Amato, E. Pomjakushina, K. Conder, Y. J. Uemura, J. M. Tranquada, H. Keller, and A. Shengelaya
Phys. Rev. Lett. 119, 087002 — Published 22 August 2017
DOI: 10.1103/PhysRevLett.119.087002
Complementary response of static spin-stripe order and superconductivity to non-magnetic impurities in cuprates

Z. Guguchia,1,2, * B. Roessli,3 R. Khasanov,1 A. Amato,1 E. Pomjakushina,4 K. Conder,4 Y.J. Uemura,2 J.M. Tranquada,5 H. Keller,6 and A. Shengelaya7,8

1Laboratory for Muon Spin Spectroscopy, Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland
2Department of Physics, Columbia University, New York, NY 10027, USA
3Laboratory for Neutron Scattering and Imaging, Paul Scherrer Institut, CH-5232 Villigen, Switzerland
4Laboratory for Developments and Methods, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
5Condensed Matter Physics and Materials Science Division, Brookhaven National Laboratory, Upton, NY 11973, USA
6Physik-Institut der Universität Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland
7Department of Physics, Tbilisi State University, Chavchavadze 3, GE-0128 Tbilisi, Georgia
8Andronikashvili Institute of Physics of I.Javakhishvili Tbilisi State University, Tamarashvili str. 6, 0177 Tbilisi, Georgia

We report muon-spin rotation and neutron-scattering experiments on non-magnetic Zn impurity effects on the static spin-stripe order and superconductivity of the La214 cuprates. Remarkably, it was found that, for samples with hole doping x ≈ 1/8, the spin-stripe ordering temperature Tsto decreases linearly with Zn doping x and disappears at y ≈ 4%, demonstrating a high sensitivity of static spin-stripe order to impurities within a CuO2 plane. Moreover, Tsto is suppressed by Zn in the same manner as is the superconducting transition temperature Tc for samples near optimal hole doping. This surprisingly similar sensitivity suggests that the spin-stripe order is dependent on intertwining with superconducting correlations.

PACS numbers: 74.72.-b, 74.62.Fj, 75.30.Fv, 76.75.+i

One of the most astonishing manifestations of the competing ordered phases occurs in the system La2−xBaxCuO4 (LBCO) [1], where the bulk superconducting (SC) transition temperature Tc exhibits a deep minimum at x = 1/8 [2–4]. At this doping level muon-spin rotation (μSR), neutron, and x-ray diffraction experiments revealed two-dimensional static charge and spin-stripe order [5–11]. The collected experimental data indicate that the tendency toward uni-directional stripe-like ordering is common to cuprates [3, 4, 12–14]. However, the relevance of stripe correlations for high-temperature superconductivity remains a subject of controversy. On the theoretical front, the concept of a sinusoidally-modulated pair-density wave (PDW) SC order, intimately intertwined with spatially modulated antiferromagnetism, has been introduced [15–17]. On the experimental front, quasi-two-dimensional superconducting correlations were observed in La1.875Ba0.125CuO4 (LBCO-1/8) and La1.48Nd0.4Sr0.12CuO4, coexisting with the ordering of static spin-stripes, but with frustrated phase order between the layers [18–23]. Recently, it was found that in La2−xSrxCuO4 (0.11 ≤ x ≤ 0.17) the 2D SC transition temperature Tc and the static spin-stripe order temperature Tsto have very similar values throughout the phase diagram [24, 25]. Moreover, a similar pressure evolution of Tc and Tsto in the stripe phase of x = 0.155 and 0.17 samples was observed. These findings were discussed in terms of a spatially modulated and intertwined pair wave function [15–17, 26]. There are also a few reports proposing the relevance of a PDW state in sufficiently underdoped La2−xSrxCuO4 [27] and YBa2Cu3O6−x [28, 29]. At present it is still unclear to what extent PDW order is a common feature of cuprate systems where stripe order occurs.

To further explore the interplay between static stripe order and superconductivity in cuprates we used non-magnetic impurity substitution at the Cu site as an alternative way of tuning the physical properties. Since the discovery of cuprate HTSs much effort was invested in the investigation of the effect of in-plane impurities. It is now well established that in cuprate HTSs nonmagnetic Zn ions suppress Tc even more strongly than magnetic ions [30–32]. Such behaviour is in sharp contrast to that of conventional superconductors. This observation led to

![FIG. 1](Color online) Zero-field (ZF) μSR time spectra A(t) for La1.875Ba0.125CuO4 (a) and La1.875Ba0.125Cu0.98Zn0.02O4 (b) recorded at various temperatures. The solid lines represent fits to the data by means of Eq. (3) of methods section.
the formulation of an unconventional pairing mechanism and symmetry of the order parameter for cuprate HTSs. In addition, in several cases a ground state with static antiferromagnetic (AF) correlations is stabilized by Zn-doping [33–38]. Up to now much less is known concerning impurity effects on the static stripe phase in cuprates at 1/8 doping. From specific heat and neutron scattering measurements it was inferred that Zn doping leads to stripe destruction [39–41]. Such an effect is very interesting and it was not predicted theoretically. However, no systematic impurity effect studies on static stripe order have been carried out up to now. Moreover, specific heat is a very indirect method to characterize the stripe phase in cuprates. Therefore, it is very important to use experimental techniques which can directly probe stripe formation and its evolution with impurity doping.

In this letter, we report on systematic muon-spin rotation ($\mu$SR), neutron scattering, and magnetization studies of Zn impurity effects on the static spin-stripe order and superconductivity in the La214 cuprates. Remarkably, it was found that in these systems the spin-stripe ordering temperature $T_{so}$ decreases linearly with Zn doping $y$ and disappears at $y \geq 4\%$. This means that $T_{so}$ is suppressed in the same manner as the superconducting transition temperature $T_c$ by Zn impurities. These results suggest that the stripe and SC orders may have a common physical mechanism and are intertwined.

In a $\mu$SR experiment, positive muons implanted into a sample serve as an extremely sensitive local probe to detect small internal magnetic fields and ordered magnetic volume fractions in the bulk of magnetic systems. Thus $\mu$SR is a particularly powerful tool to study inhomogeneous magnetism in materials [42]. Neutron diffraction experiments [43] allow to directly probe the incommensurate spin structure of spin-stripe order and thus provide crucial complementary information to the $\mu$SR technique.

Figures 1(a) and (b) show representative zero-field (ZF) $\mu$SR time spectra for polycrystalline La$_{1.875}$Ba$_{0.125}$Cu$_{1-y}$Zn$_y$O$_4$ samples with $y = 0$ and 0.02, respectively, recorded at various temperatures. For $y = 0$, damped oscillations due to muon-spin precession in internal magnetic fields are observed below $T_{so} \approx 35$ K, indicating the formation of static spin order in the stripe phase [9, 25, 44–46]. It is seen in Fig. 1(b), that for the $y = 0.02$ sample the oscillating signal appears only below $T \approx 10$ K, showing strong suppression of the static spin-stripe order with Zn doping. We have studied this novel effect systematically as a function of Zn doping.

The temperature dependence of the average internal field $B_\mu$, which is proportional to the ordered magnetic moment, is shown in Fig. 2(a) for various Zn dopings $y$. As evident from Fig. 2(a), $B_\mu(0)$, the internal magnetic field extrapolated to zero-temperature, does not de-
pend on the Zn content \(y\), while \(T_{so}\) changes substantially with increasing \(y\). Specifically, \(T_{so}\) decreases from \(T_{so} \approx 32.5 \text{ K}\) for \(y = 0\) to \(T_{so} \approx 4 \text{ K}\) for \(y = 0.04\). Figure 2(b) shows that a very similar behavior is observed for \(B_{\mu}\) measured on polycrystalline samples of the related compound \(\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{Cu}_{1−y}\text{Zn}_{y}\text{O}_{4}\). Note that the low-temperature value of \(B_{\mu}\) is enhanced by the ordering of the Nd moments. A similar suppression of \(T_{so}\) by Zn impurities was also observed in single-crystal samples of \(\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{Cu}_{1−y}\text{Zn}_{y}\text{O}_{4}\) (\(y = 0, 0.016\)). It seems that this effect is a generic feature of cuprates with static stripe order. We note that in all the above mentioned systems, despite the suppression of \(T_{so}\) with Zn doping, the magnetic volume fraction \(V_{m}\) at the base temperature stays nearly 100% [see Fig. 2(c)]. The bulk LTT structural phase transition temperature also stays nearly unaltered by Zn-doping (see supplementary Note II and supplementary Fig. S1 [42]).

The observed Zn impurity effects on \(T_{so}\) in \(\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{Cu}_{1−y}\text{Zn}_{y}\text{O}_{4}\) and \(\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{Cu}_{1−y}\text{Zn}_{y}\text{O}_{4}\) are summarised in Fig. 3. It is a remarkable finding that \(T_{so}\) linearly decreases with increasing Zn content \(y\). Such a behaviour is reminiscent of the well known linear suppression of the SC transition temperature \(T_{c}\) in cuprates [30–32]. Since the superconducting volume fraction in 1/8 doped samples is tiny and the bulk \(T_{c}\) is also very low, it is difficult to follow the SC properties of these systems as a function of Zn content. Alternatively, in Fig. 3 we plot \(T_{c}\) values for optimally doped \(\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4}\) [30–32] and \(\text{La}_{1.845}\text{Ba}_{0.155}\text{CuO}_{4}\) (see below) as a function of Zn content. Strikingly, suppression of \(T_{so}\) goes in a very similar manner as the well known impurity-induced \(T_{c}\) suppression.

We have confirmed the Zn doping effect on the static spin-stripe order by neutron diffraction experiments on single-crystal samples of \(\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{Cu}_{1−y}\text{Zn}_{y}\text{O}_{4}\) (\(y = 0, 0.016\)) [48]. The magnetic ordering wave vectors are \(\mathbf{Q}_{so} = (0.5 + \delta, 0.5, 0)\) and \((0.5, 0.5 + \delta, 0)\), i.e., they are displaced by \(\delta\) from the position of the magnetic Bragg peak in the AF parent compound \(\text{La}_{2}\text{CuO}_{4}\) [5, 6]. In Fig. 4(a) we show \(h\)-scans through the \((0.5 + \delta, 0.5, 0)\) magnetic superlattice peaks, recorded at \(T = 1.75 \text{ K}\) for the samples \(y = 0\) and 0.016. It is clear that the intensity and incommensurability do not change with Zn doping. However, \(T_{so}\) is strongly suppressed from \(T_{so} \approx 50 \text{ K}\) [5] for \(y = 0\) to \(T_{so} \approx 10 \text{ K}\) for \(y = 0.016\), as demonstrated in Fig. 4(b), where the peak intensity is shown as a function of temperature.

Going further, we studied the Zn-impurity effects on \(T_{so}\) and \(T_{c}\) in \(\text{La}_{1.845}\text{Ba}_{0.155}\text{CuO}_{4}\). This compound \((x > 1/8)\) exhibits a well defined bulk SC transition with \(T_{c} = 30 \text{ K}\) and at the same time shows static spin-stripe order \(T_{so} \approx T_{c} = 30 \text{ K}\) [24]. This enables us to study impurity effects on \(T_{so}\) and \(T_{c}\) simultaneously in the same sample. Figure 5a shows the temperature dependence of the magnetic volume fraction \(V_{m}\) extracted from ZF-\(\mu\)SR data for \(\text{La}_{1.845}\text{Ba}_{0.155}\text{Cu}_{1−y}\text{Zn}_{y}\text{O}_{4}\) (\(y = 0, 0.02\), and 0.04). The low temperature value of \(V_{m}\) increases with increasing Zn content \(y\) and reaches 100% for the highest Zn content \(y = 0.04\). On the other hand, \(T_{so}\) decreases with increasing \(y\) similar as for 1/8-doping. The values of \(T_{so}\) and \(T_{c}\) (see the supplementary Note III and supplementary Figs. S2 and S3 [42]) as a function of Zn content \(y\) are shown in Fig. 5(b). Again, with increasing \(y\) both \(T_{c}\) and \(T_{so}\) decrease linearly with the same slope, indicating that Zn impurities influence \(T_{c}\) and \(T_{so}\) in the same manner.

What is the significance of this surprising correlation? Let us start with the fact that it is unusual to have spin order occur in a hole-doped cuprate at a temperature of \(\approx 35 \text{ K}\). Just a couple of percent of hole doping is generally sufficient to wipe out antiferromagnetic order [49].
One common point of view is that antiferromagnetism and superconductivity are competing orders [50]. From that perspective, one might take the occurrence of spin-stripe order as evidence that hole-pairing and superconductivity have been suppressed. In that case, we might expect the impact of Zn-doping on $T_{\text{so}}$ to be similar to its impact on the Néel temperature in La$_2$CuO$_4$. That assumption leads to a problem, however, as experiment has demonstrated that it takes, not 4%, but ~ 40% Zn to destroy Néel order [51]. One could also take account of the fact that the Zn tends to induce static Cu spin order in its immediate neighborhood [52, 53], which, with random locations of the Zn sites, could lead, at higher Zn concentrations, to some disorder from neighboring pinned stripe domains being out of phase with one another; however, a shortening of the spin correlation length only becomes apparent with at least 3% Zn doping [41, 54], while the drop in $T_{\text{so}}$ is clear at much lower Zn concentrations.

Consider instead that previous experiments provide evidence that spin-stripe order coexists with two-dimensional superconducting correlations in LBCO-1/8 [19, 20]. Here, the superconducting and spin orders are intertwined [15]. Superconducting correlations within charge stripes must establish Josephson coupling across the spin stripes, while the spins in neighboring stripes must establish an effective exchange coupling via the fluctuating pairs in the intervening charge stripe. A Zn ion will locally suppress hole motion, thus eliminating local superconducting coherence and weakening the superconductivity [55]. Local suppression of hole hopping will also disrupt the effective exchange coupling between spin stripes, leading to a reduction in $T_{\text{so}}$.

Previous µSR studies of Zn doping in LSCO and YBa$_2$Cu$_3$O$_7$ have established the “Swiss-cheese” model: a fixed carrier density per Zn atom is removed from the superfluid density, as if each Zn removes a fixed areal fraction of the superfluid [56]. The linear relationship between $T_{\text{c}}$ and the average superfluid density, valid for underdoped through optimally-doped cuprate HTSs, then explains the reduction of $T_{\text{c}}$ with increasing Zn concentration [57]. For the stripe-ordered systems, it is plausible that both the superconducting and spin-stripe orders will respond in a similar fashion.

In conclusion, static spin-stripe order and superconductivity in cuprate systems La$_{2-x}$Ba$_x$Cu$_{1-y}$Zn$_y$O$_4$ ($x = 0.125, 0.155$) and La$_{1.48}$Nd$_{0.48}$Sr$_{1.12}$Cu$_{1-y}$Zn$_y$O$_4$ were studied by means of magnetisation, µSR, and neutron scattering experiments as a function of nonmagnetic Zn impurity concentration. High sensitivity of the static spin-stripe order temperature $T_{\text{so}}$ to impurities in the CuO$_2$ plane was demonstrated. Namely, the spin-stripe ordering temperature $T_{\text{so}}$ strongly decreases linearly with Zn doping and disappears at about 4% Zn content. More strikingly, $T_{\text{so}}$ is suppressed in the same fashion as is the superconducting transition temperature $T_{\text{c}}$ by Zn impurities. These results strongly suggest that the existence of the stripe order requires intertwining with the SC pairing correlations, such as occurs in the proposed PDW state.

The present findings should help to better understand the complex interplay between stripe order and superconductivity in cuprates. More generally, since charge and spin orders are often observed in other transition-metal oxides, investigation of impurity effects and disorder on stripe formation may become an interesting research avenue in correlated electron systems.

Acknowledgments. The µSR experiments were carried out at the πM3 beam line of the Paul Scherrer Institute (Switzerland), using the general purpose instrument (GPS). The neutron scattering experiments were carried out with the three-axis spectrometer EIGER at the Swiss Spallation Neutron Source SINQ at the Paul Scherrer Institut (PSI), Switzerland. We are grateful to S.A. Kivelson for valuable discussions. Z.G. gratefully acknowledges the financial support by the Swiss National...
Energy, Office of Basic Energy Sciences, under contract is supported at Brookhaven by the U.S. Department of Energy, Office of Basic Energy Sciences, under contract No. DE-SC0012704.

* Electronic address: zg2268@columbia.edu

[1] Bednorz, J.G., and Müller, K.A., Z. Phys. B 64, 189 (1986).
[2] Moodenbaugh, A.R., Xu, Y., Suenaga, M., Folkerts, T.J., and Shelton, R.N., Superconducting properties of \( \text{La}_{2-x}\text{Ba}_x\text{Cu}_2\text{O}_4 \). Phys. Rev. B 38, 4596 (1988).
[3] Kivelson, S.A. et al. How to detect fluctuating stripes in the high-temperature superconductors. Rev. Mod. Phys. 75, 1201 (2003).
[4] Vojta, M. Lattice symmetry breaking in cuprate superconductors: Stripes, nematics, and superconductivity. Adv. Phys. 58, 699 (2009).
[5] Tranquada, J.M., Sternlieb, B.J., Axe, J.D., Nakamura, Y., and Uchida, S., Evidence for stripe correlations of spins and holes in copper oxide superconductors. Nature (London) 375, 561 (1995).
[6] Tranquada, J.M., Axe, J.D., Ichikawa, N., Nakamura, Y., Uchida, S. and Nachumi, B., Neutron-scattering study of stripe-phase order of holes and spins in \( \text{La}_{1.84}\text{Nd}_{0.16}\text{Sr}_{0.12}\text{Cu}_2\text{O}_4 \). Phys. Rev. B 54, 7489 (1996).
[7] Abamonte, P. et al. Spatially modulated ‘Mottness’ in \( \text{La}_{2-x}\text{Ba}_x\text{Cu}_2\text{O}_4 \). Nat. Phys. 1, 155 (2005).
[8] Hucker, M. et al. Stripe order in superconducting \( \text{La}_{2-x}\text{Ba}_x\text{Cu}_2\text{O}_4 \) (0.095 ≤ x ≤ 0.155). Phys. Rev. B. 83, 104506 (2011).
[9] Luke, G.M. et al. Static Magnetic Order in \( \text{La}_{1.875}\text{Ba}_{0.125}\text{Cu}_2\text{O}_4 \). Physica C 185-9, 1175 (1991).
[10] Guguchia, Z. et al. Negative Oxygen Isotope Effect on the Static Spin Stripe Order in Superconducting \( \text{La}_{2-x}\text{Ba}_x\text{Cu}_2\text{O}_4 \) (x = 1/8) Observed by Muon-Spin Rotation. Phys. Rev. Lett. 113, 057002 (2014).
[11] M. Fujita et al., “Stripe order, depinning, and fluctuations in \( \text{La}_{1.875}\text{Ba}_{0.125}\text{Cu}_2\text{O}_4 \) and \( \text{La}_{1.875}\text{Ba}_{0.075}\text{Sr}_{0.05}\text{Cu}_2\text{O}_4 \),” Phys. Rev. B 70, 104517 (2004).
[12] Wu, T. et al. Magnetic-field-induced charge-stripe order in the high-temperature superconductor \( \text{YBa}_2\text{Cu}_3\text{O}_y \). Nature 477, 191-194 (2011).
[13] Kohsaka, Y. et al. An Intrinsic Bond-Centered Electronic Glass with Unidirectional Domains in Underdoped Cuprates. Science 315, 1380 (2007).
[14] B. Keimer, S. A. Kivelson, M. R. Norman, S. Uchida, and J. Zaanen, “From quantum matter to high-temperature superconductivity in copper oxides,” Nature 518, 179 (2015).
[15] Fradkin, E., Kivelson, S. A. and Tranquada, J. M. Colloquium: Theory of intertwined orders in high temperature superconductors. Rev. Mod. Phys. 87, 457 (2015).
[16] Himeda, A., Kato, T. and Ogata, M. Stripe States with Spatially Oscillating d-Wave Superconductivity in the Two-Dimensional t-J Model. Phys. Rev. Lett. 88, 117001 (2002).
[17] Berg, E. et al. Dynamical Layer Decoupling in a Stripe-Ordered High-\( T_c \) Superconductor. Phys. Rev. Lett. 99, 127003 (2007).
[18] Tranquada, J.M. Spins, stripes, and superconductivity in hole-doped cuprates. AIP Conference Proceedings 1550, 114 (2013).
[19] Tranquada, J.M. et al. Evidence for unusual superconducting correlations coexisting with stripe order in \( \text{La}_{1.875}\text{Ba}_{0.125}\text{Cu}_2\text{O}_4 \). Phys. Rev. B 78, 174529 (2008).
[20] Li, Q. et al. Two-Dimensional Superconducting Fluctuations in Stripe-Ordered \( \text{La}_{1.875}\text{Ba}_{0.125}\text{Cu}_2\text{O}_4 \). Phys. Rev. Lett. 99, 067001 (2007).
[21] Valla, T. et al. The Ground State of the Pseudogap in Cuprate Superconductors. Science 314, 1914 (2006).
[22] He, R.-H. et al. Energy gaps in the failed high-\( T_c \) superconductor \( \text{La}_{1.875}\text{Ba}_{0.125}\text{Cu}_2\text{O}_4 \). Nat. Phys. 5, 119-123 (2009).
[23] J. F. Ding et al., “Two-dimensional superconductivity in stripe-ordered \( \text{La}_{1-x}\text{Nd}_x\text{CuO}_{2\delta} \) single crystals,” Phys. Rev. B 77, 214524 (2008).
[24] Guguchia, Z. et al., Cooperative coupling of static magnetism and bulk superconductivity in the stripe phase of \( \text{La}_{2-x}\text{Ba}_x\text{CuO}_4 \): Pressure (\( x = 0.155, 0.17 \)) and doping (\( x = 0.11-0.17 \)) dependent studies. Phys. Rev. B 94, 214511 (2016).
[25] Guguchia, Z. et al. Tuning the static spin-stripe phase and superconductivity in \( \text{La}_{2-x}\text{Ba}_x\text{CuO}_4 \) (\( x = 1/8 \)) by hydrostatic pressure. New J. Phys. 15, 093005 (2013).
[26] Xu, Z. et al. Neutron-Scattering Evidence for a Periodically Modulated Superconducting Phase in the Underdoped Cuprate \( \text{La}_{1.905}\text{Ba}_{0.095}\text{Cu}_2\text{O}_4 \). Phys. Rev. Lett. 113, 177002 (2014).
[27] Jacobsen, H. et al. Neutron scattering study of spin ordering and stripe pinning in superconducting \( \text{La}_{1.93}\text{Sr}_{0.07}\text{Cu}_2\text{O}_4 \). Phys. Rev. B 92, 174525 (2015).
[28] Lee, P. A. Amperean Pairing and the Pseudogap Phase of Cuprate Superconductors. Phys. Rev. X 4, 031017 (2014).
[29] Yu, F. et al. Magnetic phase diagram of underdoped \( \text{YBa}_2\text{Cu}_3\text{O}_y \) inferred from torque magnetization and thermal conductivity. Proc. Natl. Acad. Sci. 113, 12667 (2016).
[30] Xiao, G., Cieplak, M.Z., Xiao, J.Q., and Chien, C.L., Magnetic pair-breaking effects: Moment formation and critical doping level in superconducting \( \text{La}_{1.85}\text{Sr}_{0.15}\text{Cu}_{1-x}\text{A}_x\text{O}_4 \) systems (\( A = \text{Fe, Co, Ni, Zn, Ga, Al} \)). Phys. Rev. B 42, 8752 (1990).
[31] Y. Fukuzumi, K. Mizushima, K. Takenaka, and S. Uchida. Universal Superconductor-Insulator Transition and \( T_c \) Depression in Zn-Substituted High/\( T_c \) Cuprates in the Underdoped Regime. Phys. Rev. Lett. 76, 684 (1996).
[32] S. Komiyama and Y. Ando, Electron localization in \( \text{La}_{2-x}\text{Sr}_x\text{CuO}_4 \) and the role of stripes. Phys. Rev. B 70, 060503(R) (2004).
[33] P. Mendels et al., “Muon-spin-rotation study of the effect of Zn substitution on magnetism in \( \text{YBa}_2\text{Cu}_3\text{O}_y \),” Phys. Rev. B 49, 10035 (1994).
[34] Akoshima, M., Koike, Y., Watanabe, I., Nagamine, K., Anomalous muon-spin relaxation in the Zn-substituted \( \text{YBa}_2\text{Cu}_{3-2x}\text{Zn}_x\text{O}_{6+y} \) around the hole concentration of 1/2 per Cu. Phys. Rev. B 62, 6761 (2000).
[35] Watanabe, I., Akoshima, M., Koike, Y., Ohira, S., Nagamine, K., Muon-spin-relaxation study on the Cu-spin state of Bi$_2$Sr$_2$Ca$_{1-y}$Y$_x$(Cu$_{1-z}$Zn$_z$)$_2$O$_{8+y}$ around the hole concentration of $\frac{1}{8}$ per Cu. Phys. Rev. B 62, 14524 (2000).

[36] Adachi, T., Yairi, S., Koike, Y., Watanabe, I., Nagamine, K., Muon-spin-relaxation and magnetic-susceptibility studies of the effects of the magnetic impurity Ni on the Cu-spin dynamics and superconductivity in La$_{2-x}$Sr$_x$Cu$_{1-y}$Ni$_y$O$_4$ with $x = 0.13$. Phys. Rev. B 70, 060504(R) (2004).

[37] T. Adachi, S. Yairi, K. Takahashi, Y. Koike, I. Watanabe, K. Nagamine, Muon spin relaxation and magnetic susceptibility studies of the effects of nonmagnetic impurities on the Cu spin dynamics and superconductivity in La$_{2-x}$Sr$_x$Cu$_{1-y}$Zn$_y$O$_4$ around $x = 0.115$. Phys. Rev. B 69, 184507 (2004).

[38] Koike, Y., and Adachi, T., Impurity and magnetic field effects on the stripes in cuprates. Physica C 481, 115 (2012).

[39] O. Anegawa, Y. Okajima, S. Tanda, and K. Yamada, Effect of spin substitution on stripe order in La$_{1.875}$Ba$_0.125$Cu$_1$-yM$_y$O$_4$ ($M = \text{Zn or Ni}$). Phys. Rev. B 63, 140506 (2001).

[40] J. Takada, T. Imukai, and M. Sato, Electronic specific heat of (La,Nd)$_{2-x}$Sr$_x$Cu$_{1-y}$Zn$_y$O$_4$ up to about 300 K. Journal of Physics and Chemistry of Solids 62, 181 (2001).

[41] Fujita, M. et al. Neutron-Scattering Study of Impurity Effect on Stripe Correlations in La-Based 214 High-$T_c$ Cuprates. J. Supercond. Nov. Magn. 22, 243 (2009).

[42] See Supplemental Material at [URL will be inserted by publisher] for details on the $\mu$SR technique and analysis, and further experimental characterizations of the samples, which includes Refs. [40, 44, 46, 47]

[43] U. Stuhr, B. Roessli, S. Gvasaliya, H.M. Rønnow, U. Filges, D. Graf, A. Bollhalder, D. Hohl, R. Bürge, M. Schidl, L. Holitzner, C. Kaegi, P. Keller and T. Mühlbacher. The thermal triple-axis-spectrometer EIGER at the continuous spallation source SINQ. Nucl. Instrum. Methods Phys. Res., Sect. A 853, 16 (2017).

[44] Nachumi, B. et al. Muon spin relaxation study of the stripe phase order in La$_{1.6}$Nd$_{0.4}$Sr$_x$CuO$_4$ and related 214 cuprates. Phys. Rev. B 58, 8760-8772 (1998).

[45] J. Arai, T. Ishiguro, T. Goko, S. Igaya, K. Nishiyama, I. Watanabe, and K. Nagamine, Journal of Low Temperature Physics 131, 375 (2003).

[46] Suter, A. and Wojtek, B.M. Musriti: a free platform-independent framework for $\mu$SR data analysis. Physics Procedia 30, 69-73 (2012).

[47] M.K. Crawford, R.L. Harlow, E.M. McCarron, W.E. Farre, J.D. Axe, H. Chou, and Q. Huang, Lattice instabilities and the effect of copper-oxygen-sheet distortions on superconductivity in doped La$_2$CuO$_4$. Phys. Rev. B 44, 749 (1991).

[48] Note that this is the nominal composition of the crystals, based on the starting materials; the actual composition could differ slightly from that of the polycrystalline samples discussed earlier.

[49] M. Matsuda, M. Fujita, K. Yamada, R. J. Birgeneau, Y. Endoh, and G. Shirane, “Electronic phase separation in lightly-doped La$_{2-x}$Sr$_x$CuO$_4$”. Phys. Rev. B 65, 134515 (2002).

[50] S. Sachdev, “Quantum Criticality: Competing Ground States in Low Dimensions,” Science 288, 475 (2000).

[51] O. P. Vajk, P. K. Mang, M. Greven, P. M. Gehring, and J. W. Lynn, “Quantum Impurities in the Two-Dimensional Spin One-Half Heisenberg Antiferromagnet,” Science 295, 1691 (2002).

[52] A. V. Mahajan, H. Alloul, G. Collin, and J. F. Marucco, $^{63}$Y NMR Probe of Zn Induced Local Moments in YBa$_2$(Cu$_{1-y}$Zn$_y$)$_3$O$_{6+y}$.” Phys. Rev. Lett. 72, 3100 (1994).

[53] M.-H. Julien et al., $^{63}$Cu NMR Evidence for Enhanced Antiferromagnetic Correlations around Zn Impurities in YBa$_2$Cu$_3$O$_7$.” Phys. Rev. Lett. 84, 3422 (2000).

[54] H. Kimura, K. Higashi, H. Matsushita, K. Yamada, Y. Endoh, S.-H. Lee, C.F. Majkrzak, R. Erwin, G. Shirane, M. Greven, Y.S. Lee, M.A. Kastner, and R.J. Birgeneau, Neutron-scattering study of static antiferromagnetic correlations in La$_{2-x}$Sr$_x$Cu$_{1-y}$Zn$_y$O$_4$. Phys. Rev. B 59, 6517 (1999).

[55] C.M. Smith, A.H. Castro Neto, and A.V. Balatsky, $T_c$ suppression in co-doped striped cuprates. Phys. Rev. Lett. 87, 177010 (2001).

[56] Nachumi, B. et al. Muon Spin Relaxation Studies of Zn-Substitution Effects in High-$T_c$ Cuprate Superconductors. Phys. Rev. Lett. 77, 5421 (1996).

[57] Y. J. Uemura et al. Universal Correlations between $T_c$ and $n_s/m^*$ (Carrier Density over Effective Mass) in High-$T_c$ cuprate superconductors. Phys. Rev. Lett. 62, 2317 (1989).