Magnetic field-effect on static spin correlation in stripe ordered phase of La$_{2-x}$Ba$_x$CuO$_4$

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Abstract.

Magnetic field-effect on spin-density-wave (SDW) order was studied for the single crystals of La$_{2-x}$Ba$_x$CuO$_4$ with $x=0.10$ ($T_c=24$ K) and $x=0.125$ ($T_c<5$ K) by neutron-scattering measurements. At zero field, incommensurate peaks from both SDW and charge-density-wave (CDW) orders were observed below 40 K (50 K) in the former (latter) sample. Applying the field of 10 T perpendicular to the CuO$_2$ plane, the magnetic intensity in the $x=0.10$ sample was enhanced with the rate of 20% of that at 0 T, while in the $x=0.125$ sample no obvious field-effect on SDW order was confirmed under the field up to 10 T. These results suggest that the magnetic field induces enhancement of static SDW order in the superconducting sample and does not affect the well-stabilized SDW order in the non-superconducting sample of the LBCO system at $x\sim 1/8$.

1. Introduction

High-$T_c$ superconductivity can emerge when charge carriers are doped into an antiferromagnetic Mott insulator. For the last two decades, enormous efforts, theoretical and experimental, have been made to attempt to understand the mechanism of the superconductivity. Neutron scattering studies showed intimate relation between magnetism and superconductivity [1]. In hole-doped La$_{2-x}$Sr$_x$CuO$_4$ (LSCO), the hole doping rapidly suppresses the antiferromagnetism and induces incommensurate (IC) spin fluctuations that exist entire superconducting phase. Furthermore, in the Nd-doped LSCO system, the evidence of IC charge-density-wave (CDW) order as well as spin-density-wave (SDW) order was observed [2]. Then the stripe model was proposed, in which the hole-free spin domains are segregated by one-dimensional stripes of hole-rich region.

Recent neutron-scattering study under magnetic fields revealed that in the LSCO with $x\sim 1/8$ where a bulk superconductivity and static IC magnetic order coexist, the IC magnetic order is enhanced by applying magnetic fields with suppressing the superconductivity [3,4]. Moreover, an external magnetic field induces slow spin fluctuations below the gap energy of $\sim 6$ meV [5] in the optimally doped LSCO. In the framework of the stripe model, these results are understood as that the stripe fluctuations are suppressed by a magnetic field and the orders competitively
La$_{2-x}$Ba$_x$CuO$_4$, $T=3$K

![Graph showing the incommensurate peak from SDW order of (a) La$_{1.90}$Ba$_{0.10}$CuO$_4$ and (b) La$_{1.875}$Ba$_{0.125}$CuO$_4$ measured at 3 K under magnetic field of 0 and 10 T.]

**Figure 1.** Incommensurate peak from SDW order of (a) La$_{1.90}$Ba$_{0.10}$CuO$_4$ and (b) La$_{1.875}$Ba$_{0.125}$CuO$_4$ measured at 3 K under magnetic field of 0 and 10 T.

induces instability of superconductivity. On the contrary, no field-effect on both IC peaks from SDW and CDW orders was observed in the stripe ordered phase of La$_{1.45}$Nd$_{0.4}$Sr$_{0.15}$CuO$_4$ up to 7T [6].

To shed more light on the relationship between the stripe order and the superconductivity, we investigated field-effect on the static SDW order in the La$_{2-x}$Ba$_x$CuO$_4$ system with $x=0.10$ and 0.125 by neutron-scattering measurements. In the $x=0.10$ sample, bulk superconductivity appears with the transition temperature $T_c$(onset) = 24 K, while the $x=0.125$ sample show no trace of bulk superconductivity down to $\sim$2 K. In contrast to the no obvious IC peak from CDW order in LSCO [7], SDW and CDW orders coincidentally appears in the present LBCO system as the temperature decreases. Thus, the field-effect on the stripe order and its relevance to the superconducvity can be more directly investigated through a comparative study on these two samples.

2. Experimental Details
A sizable single crystals of LBCO with $x=0.10$ and 0.125 were grown by a traveling-solvent floating-zone method. Both samples are the same crystals as that used for a previous neutron scattering studies under a zero magnetic field [8,9]. Structural phase transition between low-temperature-orthorhombic and low-temperature-tetragonal phase takes place at $\sim$50 K and $\sim$60 K in the $x=0.10$ and 0.125 samples, respectively.

Elastic neutron scattering measurements were performed on the thermal triple-axis spectrometer TAS-2 installed in the guide hall of JRR-3 at Japan Atomic Energy Agency. We used incident neutron energy of 14.7 meV with collimation sequences of 17'-80'-40'-80'. Contamination form higher-order wavelengths in the neutron beams was eliminated by pyrolytic graphite filters placed before and after sample. We mounted each single crystal with the CuO$_2$ planes in the horizontal scattering plane. Then magnetic field is applied perpendicular to the CuO$_2$ plane by using a split-type cryocooled superconducting magnet. In this paper, all crystallographic indexes are denoted as $(h k 0)$ in the tetragonal $I4/mmm$ notation.
3. Results and Discussion

Profiles of IC peak from the SDW order measured at 0 and 10 T are shown in Fig. 1. In zero field, IC peaks were found to be centered at (0.5 0.5±0.110 0) in the x=0.10 and (0.5 0.5±0.118 0) in the x=0.125 sample, respectively. In both samples, the peak-width is close to the resolution limited value, indicating that the correlation length of SDW order is ∼200 Å in the CuO$_2$ planes.

Applying the field of 10 T perpendicular to the CuO$_2$ plane, the magnetic intensity in the x=0.10 sample is enhanced with the rate of 20% of that at 0 T. On the other hand, in the x=0.125 sample no obvious enhancement of SDW order was observed under the field up to 10 T. The width and the position of SDW peaks in two samples do not change against the magnetic field within the experimental resolution.

In Fig. 2, the temperature-dependence of the magnetic peak intensity is shown. Intensity was measured with increasing the temperature after a field-cooling process from the structural phase transition temperatures. In zero-field, the magnetic signal starts to appear at $T_m$ ∼40 K and ∼50 K in the x=0.10 and 0.125 samples with cooling the temperature. As seen in the figure, in the x=0.10 sample, applying magnetic field of 10 T enhances the existing intensity from SDW order in the entire temperature range below $T_m$. The field-enhanced magnetic intensity with no field-effect on $T_m$ is consistent with the previously reported results for superconducting LSCO and LCO [4,10], in which no clear evidence of CDW order was observed. On the contrary, in the x=0.125 sample, the intensity measured under the field of 10 T shows a same temperature dependence with that at 0 T, meaning no field-effect on the SDW order in non-superconducting LBCO. The field-dependence of the peak intensity for La$_{1.90}$Ba$_{0.10}$CuO$_4$ at 3K is shown in Fig. 3. The intensity gradually increases with applying the magnetic field, suggesting the field-induced stabilization of static stripe order. We note that the evidence of stabilization of charge stripe order in La$_{1.90}$Ba$_{0.10}$CuO$_4$ was reported from the resistivity measurement [11].

We now compare the field-effect on the SDW order in LBCO with those in LSCO. In the present study, the enhancement of magnetic intensity by magnetic fields was confirmed for the LBCO with x=0.10 sample. However, the relative enhanced intensity to the zero-field signal is much small compared with that in LSCO with x=0.10 measured at a comparable temperature and a magnetic field, although $T_c$ in two systems is comparable. Analogously, no field-effect was
observed in the LBCO with $x=0.125$ sample, while magnetic fields strongly enhances the SDW intensity in the LSCO with $x=0.12$ ($T_c=12$ K). [3] Furthermore, the temperature dependence of the intensity under the field is almost same with that at zero-field in the LBCO but different in the LSCO with $x=0.10$. These results suggest that the static spin correlations are effectively stabilized in the LSCO system by magnetic fields. This difference would be understood through the difference in the stability of stripe order and/or in the volume fraction of the stripe ordered region at zero-field in two systems [12]. Field-independent $T_m$ suggests that the additional SDW order region is induced by the magnetic field, and the competing superconductivity is suppressed. Magnetic intensity in the LSCO with a small stripe ordered region at zero-field could be more effectively enhanced by the magnetic field than that in LBCO system with well-stabilized SDW order.

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4. References
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