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μSR and thermal conductivity studies on inhomogeneity of the impurity- and field-induced magnetism and superconductivity in high-T_c cuprates

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Abstract

The inhomogeneity of the impurity- and field-induced magnetic order and superconductivity has been investigated in the hole-doped $La_{2-x}Sr_xCuO_4$ (LSCO), $La_{2-x}Ba_xCuO_4$ (LBCO) and the electron-doped $Pr_{1-x}LaCe_xCuO_4$ (PLCCO). For the hole-doped cuprates, it has been found from the muon-spin-relaxation measurements that both Zn and Ni impurities tend to develop a magnetic order and to destroy the superconductivity around themselves not only around p (the hole concentration per Cu) = 1/8 but also at $x = 0.15$ and 0.18 in LSCO, though the development of the magnetic order by Zn is more marked than by Ni. Moreover, it has been found from the thermal conductivity measurements that the development of the magnetic order by the application of magnetic field is marked not just at $p = 1/8$ but in the neighborhood of $p = 1/8$ in LSCO and LBCO. The impurity- and field-induced magnetic order in the hole-doped cuprates can be interpreted as being due to pinning of the dynamical stripes of holes and spins by impurities and vortex cores in the CuO_2 plane, respectively. For the electron-doped PLCCO with $x = 0.14$, on the contrary, no impurity-induced magnetic order has been observed. The reason is discussed.
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1. Introduction

Since the discovery of the high-T_c superconductivity in the cuprates, impurity effects on the superconductivity and physical properties have been investigated vigorously. For the hole-doped high-T_c cuprates, it is well known that the superconductivity is suppressed by the non-magnetic impurity Zn^{2+} (the spin quantum number $S = 0$) more strongly than by the magnetic impurity Ni^{2+} ($S = 1$) [1,2]. As for the inhomogeneity in the partially Zn-substituted samples, the so-called "Swiss cheese" model has been proposed by Nachumi et al. [3] where each Zn introduced in the CuO_2 plane is regarded as producing a non-superconducting region around itself like a hole in Swiss cheese. In fact, the local destruction of superconductivity around Zn has been pointed out from the scanning-tunneling-microscopy measurements in the partially Zn-substituted $Bi_2Sr_2CaCu_2O_{8+\delta}$ [4]. However, the magnetic state around Zn has not been clarified. On the other hand, it is known that the so-called 1/8 anomaly, namely, the anomalous suppression of superconductivity at p (the hole concentration per Cu) ~1/8 becomes marked through the partial substitution of Zn for Cu in $La_{2-x}Sr_xCuO_4$ (LSCO) [5]. This is understood in terms of the stripe-pinning model [6–8], where dynamically fluctuating stripes of spins and holes are regarded as existing and being easily pinned by such an impurity as Zn especially around $p = 1/8$, leading to the static stabilization of a stripe order of spins and holes, namely, both magnetic and charge order and to the suppression of superconductivity. Accordingly, it attracts interest whether the stripe-pinning model is applicable to a wide range of p in the hole-doped cuprates and also electron-doped ones or not.

According to the recent neutron scattering experiments in magnetic fields by Katano et al. [9] and Lake et al. [10], the intensity of the incommensurate magnetic Bragg peak corresponding to the static stripe order is markedly enhanced for $x = 0.10$ in LSCO by the application of magnetic field parallel to the c axis, while the enhancement is observable but small for $x = 0.12$. It also attracts interest whether the field-induced magnetic order is understood in terms of the stripe-pinning model or not.

In this paper, we review our experimental works on the effects of Zn and Ni impurities on the magnetic state and superconductivity in the hole-doped LSCO [11–13] and the electron-doped $Pr_{1-x}LaCe_xCuO_4$ (PLCCO) [14] using the muon-spin-relaxation (μSR) and magnetic susceptibility measurements. Moreover, we review our experimental works on the field-induced magnetic order in LSCO [15,16] and $La_{2-x}Ba_xCuO_4$ (LBCO) using the thermal conductivity measurements.

2. Experimental

Sintered samples of $La_{2-x}Sr_xCu_{1-y}(Zn,Ni)_yO_4$ and $Pr_{1-x}LaCe_xCu_{1-y}(Zn,Ni)_yO_4$ for the μSR and magnetic susceptibility measurements were prepared by the solid-state reaction method, changing y finely up to 0.10. Single crystals of $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$ and LBCO for the thermal conductivity measurements were grown by the traveling-solvent floating-zone method [15,17]. The μSR measurements were carried out at the RIKEN-RAL Muon Facility at the Rutherford-Appleton Laboratory in the UK, using a pulsed positive surface muon beam. The thermal conductivity measurements in magnetic fields were performed by a conventional steady-state method in magnetic fields up to 14 T at the High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University. The magnetic susceptibility measurements were carried out using a SQUID magnetometer.

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