MAGNETIZATION OF CHARGE-ORDERED La$_{2-x}$Sr$_x$NiO$_{4+\delta}$

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We report magnetization measurements on La$_{2-x}$Sr$_x$NiO$_{4+\delta}$ single crystals, with $0 \leq x \leq 0.5$. Glassy behaviour associated with the formation of spin-charge stripes, and a separate spin-glass phase at low temperatures were observed. We have also found a ‘memory effect’ in the magnetic field – temperature history, which is found to be suppressed in the low temperature spin state of the $x = 0.33$ crystal.

Spin and charge ordering in the form of stripes has been observed in a number of doped antiferromagnets, particularly in layered transition-metal oxides such as cuprates and nickelates[1]. The possibility that stripe correlations play an important role in the mechanism of high-$T_c$ superconductivity makes it important to understand the properties of the stripe phase.

In La$_{2-x}$Sr$_x$NiO$_{4+\delta}$ (LSNO) the charges order into periodically spaced lines of charges that lie at $45^\circ$ to the Ni-O bonds[2]. At lower temperatures the Ni$^{2+}$ spins order antiferromagnetically between the charge-stripes that act as antiphase domain walls to the magnetic order[3]. These studies have also revealed commensurability effects occurring only in the 1/3 and 1/2 doped materials[4,5]. Previous work has also found a spin glass state exists at low temperatures in LSNO[6]. Here we report magnetization measurements that reveal other types of glassy behaviour in these materials, including a field ‘memory effect’ in the spin glass state.

We performed magnetization measurements on single crystals of La$_{2-x}$Sr$_x$NiO$_{4+\delta}$ using a SQUID magnetometer (Quantum Design). The single crystals were grown by the floating-zone technique[7] from high purity oxides. These crystals have a typical size of $5 \times 5 \times 2$ mm. The oxygen content was determined by thermogravimetric analysis.

Figure 1 shows a set of typical results, obtained from a sample with $x = 0.275$ with a measuring field of 500 Oe applied parallel to the $ab$ plane. The charge and spin ordering temperatures are indicated. A spin glass phase at low temperature ($T_{SG1} \approx 40$ K) is signalled by a clear divergence of the zero-field-cooled (ZFC) and field-cooled (FC) magnetization. However, glassy behaviour is seen to extend to much higher temperatures: a smaller ZFC/FC splitting only vanishes at a temperature $T_{SG2}$ between $T_{SO}$ and $T_{CO}$. In the case of $x = 0.5$, where $T_{SO} \sim 90$ K and $T_{CO} \sim 480$ K, the ZFC and FC curves did not close up until well above $T_{SO}$. Hence the $T_{SG2}$ feature appears to be correlated with charge-ordering.

In the spin glass phase of LSNO we observed all the materials to have an effective ‘memory’ of their temperature-field history in the $ab$ plane. We observed this by cooling the sample in a field of 500 Oe to $T_0$ ($< T_{SG1}$), removing the field, cooling to 2 K, and then measuring in zero field while warming. Apart from the $x = 0.333$ sample, we observe a stable ($> 1$ hr) induced magnetic signal that decreased in size above $T_0$, and finally levels off to a constant value at $T_{SG1}$, see figure 2. With $x = 0.333$, the signal is small at low temperatures, but rises sharply just below $T_{SG1} \approx 50$ K, corre-
Figure 1. A typical set of ZFC and FC data for a LSNO material, showing the convergence of the FC and ZFC magnetization between $T_{SO}$ and $T_{CO}$. The charge ordering, $T_{CO}$, (as confirmed by x-ray scattering[6]) spin ordering $T_{SO}$, (as confirmed from neutron diffraction) and spin glass temperatures, $T_{SG1}$ and $T_{SG2}$, are indicated.

Figure 2. The signal induced by field-cooling to the temperature $T_0$ indicated in the key, then cooling to 2 K in zero field, and measuring while warming in zero field. The spin-reorientation temperatures of the $x = 0.333$ and $x = 0.5$ samples are indicated.

Our results further add to the knowledge of the glassy behaviour associated with charge-stripe ordering in LSNO. The existence of two apparently different glassy regimes, as well as other unusual field-temperature hysteretic effects, shows that the glassy properties of stripe phases are quite different to those observed in many other spin-glass materials. Further work needs to be carried out to determine the nature of these effect in fields parallel to c.

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