Evolution of spin gap structure in underdoped LSCO

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Neutron scattering studies for high-T_c cuprates have revealed that a well-defined gap opens at low temperature in the energy spectra, which is called "spin gap", in LSCO ($La_{2-x}Sr_xCuO_4$) and YBCO ($YBa_2Cu_3O_{6+y}$). As for LSCO, the spin gap is observed only around the optimum doping concentration $0.15 \leq x \leq 0.18$ [1]. On the other hand, the spin gap of YBCO appears in the wide underdoped region $0.5 \leq y \leq 0.95$ [2]. The invisibility of spin gap in underdoped LSCO is a longstanding issue. To solve the issue, we have carried out a systematic series of inelastic neutron scattering experiments on single crystals of LSCO with x lower than optimal doping.

Single crystals of LSCO with $x = 0.125$, 0.13, 0.135, 0.14, 0.15 were grown by a traveling solvent floating zone method. For these crystals, we estimated the superconducting transition temperature T_c by the shielding signals and the Sr concentration x by the inductively coupled plasma (ICP) analysis. The values of x and T_c are summarized in Table. 1 and are almost consistent with the previous results. Neutron scattering experiments were performed with the triple-axis spectrometer TOPAN installed at JRR-3M. We selected the final energy of 13.5 meV with the horizontal collimator sequence of 40′-30′-30′-80′. In order to gain sufficient intensity, we mounted single crystals with total weight of more than 2.5 cc (=17 g) for each concentration.

Table 1. x and T_c in $La_{2-x}Sr_xCuO_4$

sample	Sr x	T_c
$x = 0.15$	0.142(8)	37.6 K
$x = 0.14$	0.130(5)	36.3 K
$x = 0.135$	0.125(5)	33.7 K
$x = 0.13$	0.120(6)	30.9 K
$x = 0.125$	0.115(6)	25.8 K

In the low energy region ($\omega \leq 10$ meV), the spin excitation appears at incommensurate (IC) positions $Q = (\frac{1}{2} \pm \delta\ \frac{1}{2}\ 0)$, $(\frac{1}{2}\ \frac{1}{2} \pm \delta\ 0)$ in the high-temperature tetragonal (HTT) notation. Figure 1 shows the energy spectra of the dynamical magnetic susceptibility $\chi''(Q_\delta, \omega)$ at the IC peak position $Q = Q_\delta$ below 10 K. As for $x \geq 0.135$, the clear spin gap were observed and its structure is almost unchanged. While, for $x = 0.125$ and 0.13, the spectrum shows an upturn behavior around 3 meV. This sudden change of the spectrum around $x = 0.13$ indicates that the low-energy additive state appears with keeping the gap structure in $x \leq 0.13$. In addition, we found weak elastic magnetic peaks for $x = 0.13$, and the peaks becomes sharp and strong for $x = 0.125$, which is coincident with the appearance of the additional state. Therefore, the spin gap appears robust in $0.125 \leq x \leq 0.15$ and the low-energy additional state emerges near $x \sim 1/8$.

References

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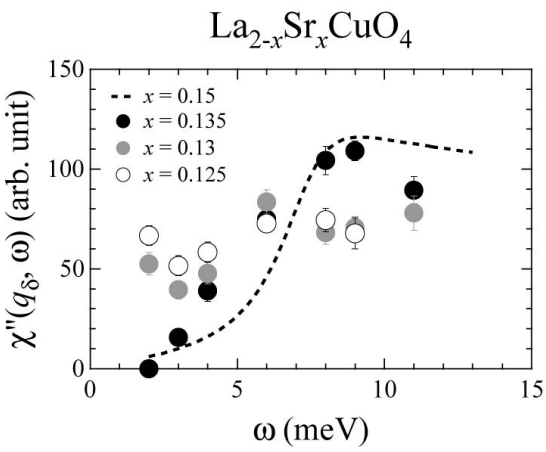

Fig. 1. Energy spectra of the dynamical magnetic susceptibility $\chi''(Q_\delta, \omega)$ at the incommensurate peak position $Q = Q_\delta$ below $T = 10$ K for $La_{2-x}Sr_xCuO_4$ ($x = 0.125, 0.13, 0.135, 0.15$).