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μ^+SR on $(La_{1.85-x}Nd_x)Sr_{0.15}CuO_4$ *

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Below 30 K, magnetic order was found in $La_{1.85-x}Nd_xSr_{0.15}CuO_4$ with x ranging between 0.30 and 0.60. This order occurs in the low temperature tetragonal phase. Below 5 K, the interaction of Nd and Cu moments modifies the magnetic order in the Cu–O planes leading to an increase of the muon spin rotation frequency and the transverse damping rate. Even down to 0.1 K, considerable spin dynamics is observable.

La_2CuO_4 has a magnetically ordered ground state with a Néel temperature of $T_N = 300$ K. At low temperatures, the crystal structure is orthorhombic (LTO phase) but the difference between the lattice constants a and b is only of the order of 1%. The most favourable site, where the muon comes to rest in this structure, is next to the apical oxygen ion (see, e.g., [1]).

Hole doping via substitution of La by Sr quickly destroys the magnetic order in the Cu–O planes and superconductivity appears for $La_{2-y}Sr_yCuO_4$ at $y = 0.08$. The maximum of the superconducting transition temperature is found for $y = 0.15$. Keeping the Sr concentration constant at the value of $y = 0.15$, further substitution of La by Nd was done. There is a competition between the transition to the superconducting state and a low temperature structural phase transition (see phase diagram in fig. 1). For $x > 0.18$ the system $La_{1.85-x}Nd_xSr_{0.15}CuO_4$ exhibits a low temperature tetragonal (LTT) phase [2,3]. The transition temperature T_{LT} varies systematically with the Nd concentration in the range from $x = 0.18$ to $x = 0.80$. No bulk superconductivity is found in the LTT phase. In addition to the change in ion radius between La and Nd, which is supposed to be the cause for the LTO–LTT transition, the Nd^{3+} ions introduce localized magnetic moments on the sites of the diamagnetic La^{3+} ions. The interplay of these moments with the copper moments and the interaction of the copper

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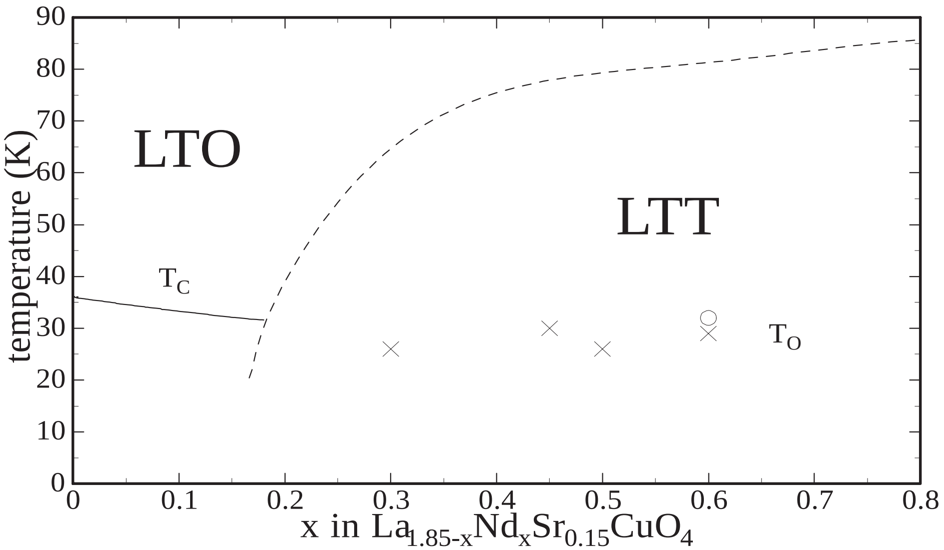

Fig. 1. Phase diagram of $La_{1.85-x}Nd_xSr_{0.15}CuO_4$. The crosses mark the onset temperature T_O of magnetic order as derived from our experiments, the circle marks T_O as derived from Mössbauer data [4].

moments in the Cu–O planes among themselves is under discussion. Some evidence for slow paramagnetic relaxation or local magnetic order below 32 K has previously been derived from the magnetic hyperfine splittings seen in the Mössbauer spectra of Fe and Sn doped $La_{1.25}Nd_{0.60}Sr_{0.15}CuO_4$ [4]. In neutron diffraction experiments on $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$, superlattice peaks have been found. A possible explanation assuming antiferromagnetic *stripes* in the Cu–O planes was given by Tranquada et al. [5].

In order to clarify the origin of the magnetic hyperfine interaction we have examined the system $La_{1.85-x}Nd_xSr_{0.15}CuO_4$ using μ^+SR. The powder samples with x ranging from 0.30 to 0.60 were prepared by standard solid state reaction. We performed ZF, LF and TF experiments at the GPS and LTF spectrometers of PSI, Switzerland. The temperature was varied between 0.1 K and 100 K, fields up to 1 T were applied. For comparison, a sample of $La_{1.7}Nd_{0.3}CuO_4$ was also examined.

The found nuclear damping rate of 0.188 μs^{-1} is compatible with the apical oxygen muon site. Up to 100 K, there are no signs for muon diffusion. When decreasing temperature, there is an increase of electronic damping due to a slowing down of the moments (see fig. 2). The structural phase transition (LTO–LTT) takes place at about 75 K as confirmed by X-ray diffraction [2]. The small change in the lattice parameters connected to this transition is not reflected by our experiments indicating that no strong changes of the electronic environment of the muon result from the transition. Similarly Mössbauer spectra also do not reveal any changes at the LTO–LTT transition [4].

Below 30 K, the electronic spin system becomes static in the time window of the μ^+SR with spontaneous muon spin rotations (see fig. 3). In powder samples, the

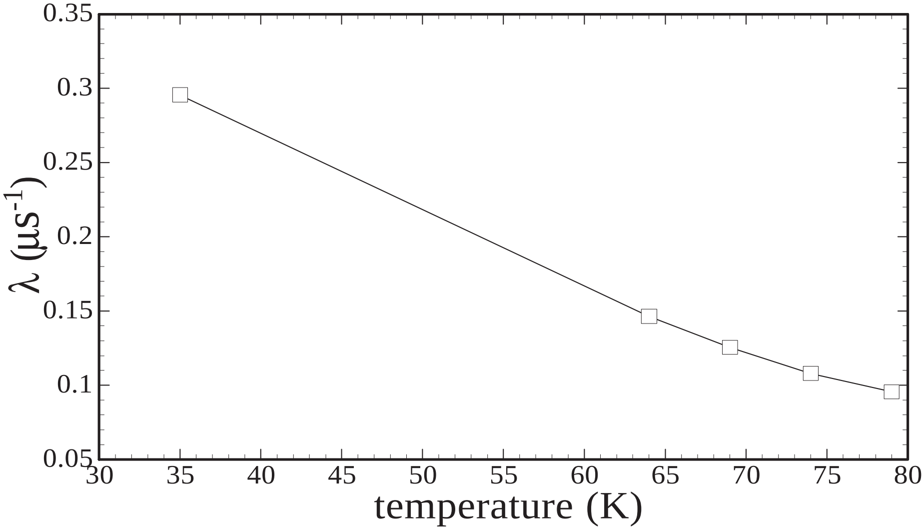

Fig. 2. Temperature dependence of the electronic damping rate λ in the sample $La_{1.4}Nd_{0.45}Sr_{0.15}CuO_4$.

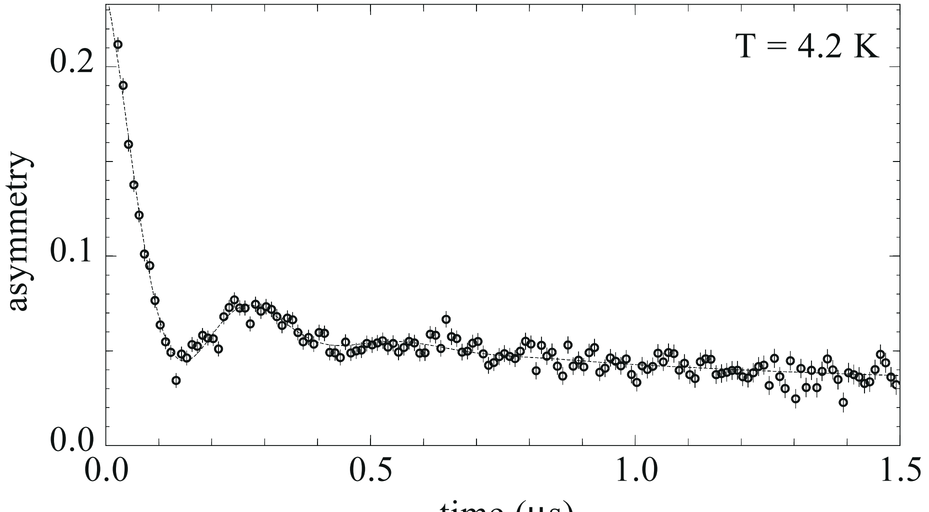

Fig. 3. Asymmetry plot of $La_{1.4}Nd_{0.45}Sr_{0.15}CuO_4$ at $T = 4.2$ K.

direction of the field at the muon site is isotropically distributed, which was taken into account by the used fit function:

$$A(t) = A_0\,\mathrm{GKT}(t)\left[\frac{2}{3}\exp(-R_2 t)\,\cos(2\pi\nu t) + \frac{1}{3}\exp(-R_1 t)\right].$$

The Gaussian Kubo–Toyabe function $\mathrm{GKT}(t)$ describes the nuclear damping. The term in brackets represents the electronic part of the interactions, R_1 denotes the

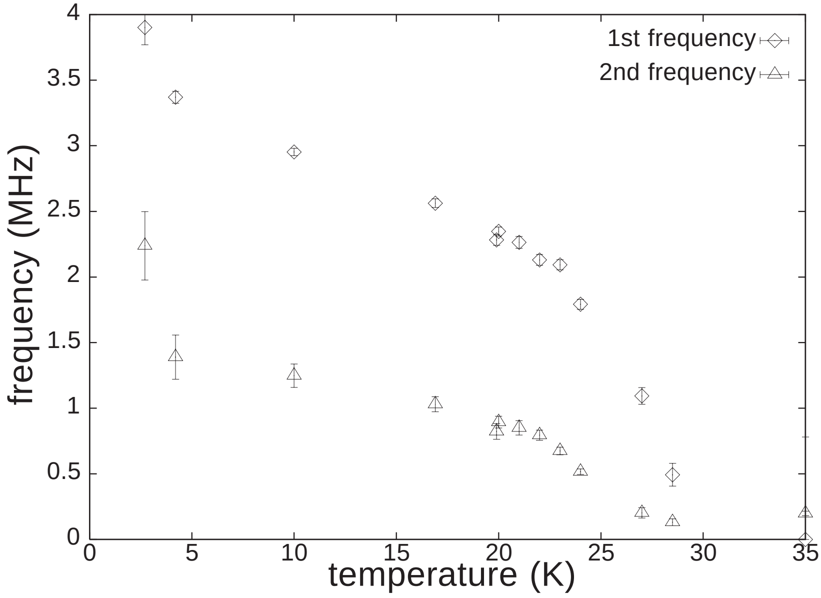

Fig. 4. Temperature dependence of the two muon spin rotation frequencies for the sample $La_{1.4}Nd_{0.45}Sr_{0.15}CuO_4$.

Table 1
Muon spin rotation frequencies at 10 K, asymmetries of the two signals and ordering temperatures T_O.

Nd content	1st signal		2nd signal		Ordering temp.
x	freq. (MHz)	asym.	freq. (MHz)	asym.	T_O (K)
0.30	2.80 ± 0.05	0.10 ± 0.01	1.12 ± 0.07	0.11 ± 0.01	26 ± 2
0.45	2.95 ± 0.03	0.15 ± 0.01	1.25 ± 0.09	0.08 ± 0.01	30 ± 2
0.50	2.95 ± 0.05	0.04 ± 0.01	1.70 ± 0.05	0.11 ± 0.01	26 ± 2
0.60	3.15 ± 0.06	0.05 ± 0.01	2.00 ± 0.10	0.09 ± 0.01	29 ± 2

longitudinal relaxation rate, R_2 the transverse relaxation rate and ν the muon spin rotation frequency. At least two of these powder sample signals had to be taken for good agreement with the spectra. This is most probably due to different ions occupying the La sites next to the muon leading to a broad distribution of the hyperfine field. The relative ratio of the asymmetries for the two signals varies insystematically with the samples. However, for each sample both asymmetries could be kept constant for the whole temperature range.

The temperature dependence of the frequencies is plotted in fig. 4. The values of the two frequencies at $T = 10$ K for the different Nd concentrations, the asymmetries of the two signals and the estimated ordering temperature T_O are given in table 1. The rotating signals are attributed to the onset of magnetic order in the Cu–O planes, although the frequencies do not reach the same values as in La_2CuO_4 [6,7]. We re-

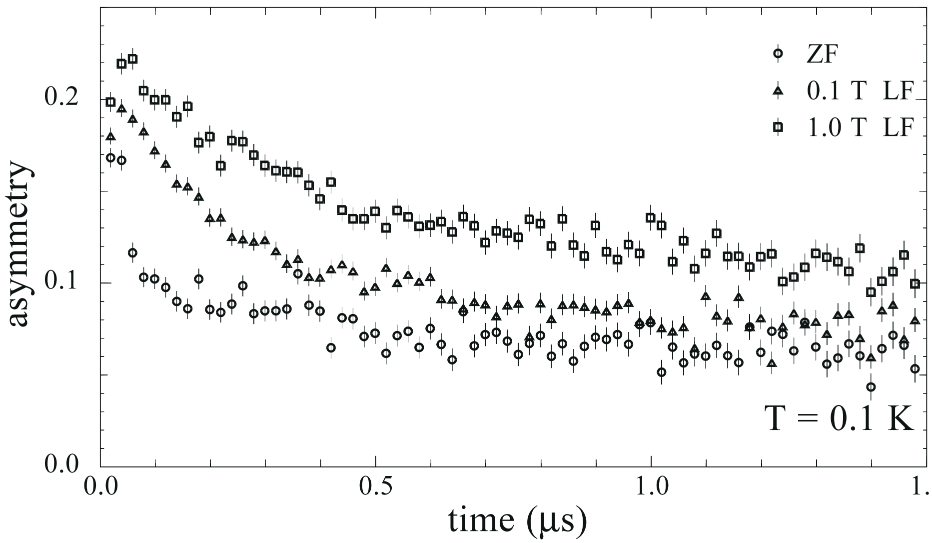

Fig. 5. LF decoupling experiment on $La_{1.25}Nd_{0.6}Sr_{0.15}CuO_4$ at $T = 0.1$ K.

late this difference in the rotation frequencies to Sr doping and not to Nd doping, as can be seen in the spectra of the sample $La_{1.7}Nd_{0.3}CuO_4$, which resemble very much those of La_2CuO_4: in $La_{1.7}Nd_{0.3}CuO_4$, spontaneous muon spin rotation is observed below about 285 K (compare: $T_N = 300$ K for La_2CuO_4); the saturation value of the frequency of about 5 MHz is reached very fast.

Below 5 K, a further increase is found in the muon rotation frequencies and in the damping rates for the $La_{1.85-x}Nd_xSr_{0.15}CuO_4$ samples. This effect is stronger for the samples with higher Nd concentrations. Thus we interpret it with an increase of coupling between the Nd and the Cu moments. This may lead to a change in the ordered structure of the copper moments reflected in an increase of the field at the muon site. These results are supported by specific heat data revealing a Schottky anomaly at low temperatures, which is also more pronounced for higher Nd concentrations [8].

The transverse damping rate R_2 of the rotating signal rises from about 0.3 μs^{-1} at 30 K to more than 10 μs^{-1} below 4 K. Decoupling experiments in applied longitudinal fields, however, reveal that even at 0.1 K the electronic spin system does not become totally static (see fig. 5), that means no static order of the Nd moments is reached down to 0.1 K.

Our μ^+SR experiments have proved the existence of magnetic order in the Cu–O planes in the system $La_{1.85-x}Nd_xSr_{0.15}CuO_4$ with $0.30 \leqslant x \leqslant 0.60$. This magnetic order seems to be connected with the LTT phase. The ordering temperature T_O is, however, significantly below the LTO–LTT phase transition. Our values for T_O are in agreement with the values from Mössbauer experiments [4] and are close to the crossover temperature of the superconducting T_C and the LTO–LTT transition temperature in the phase diagram (see fig. 1). This coincidence may give rise to speculations about the counterplay of magnetism and superconductivity in these compounds.

At low temperatures the interactions between Nd and Cu moments modify the magnetic order in the Cu–O planes leading to a canting of the copper moments or even to a coupling of neighbouring planes. Considerable spin dynamics is still found down to lowest temperatures. Whether this is caused by the interaction of Nd with the strongly correlated conduction electron system [9] and/or with the dynamics of stripe correlations [5] needs further investigation.

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