LOCAL MAGNETISM IN SUPERCONDUCTING YBa$_2$Cu$_3$O$_{6+x}$

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Oxygen-deficient YBa$_2$Cu$_3$O$_{6+x}$ samples were investigated by the muon spin rotation technique in zero external field. In an intermediate oxygen concentration region we find strongly relaxing $\mu$SR signals indicating the existence of internal magnetic fields. The strongly relaxing signals were observed only in samples with superconducting transition temperatures below 50 K. As an interpretation of the data we suggest that magnetic ordering and superconductivity coexist in these samples within regions of extensions of a few lattice constants, but not necessarily on the same sites.

1. Introduction

There is strong experimental evidence for an intimate connection between magnetism and superconductivity in the high temperature superconductors. Muon spin rotation and neutron scattering proved the existence of antiferromagnetic order in the insulating phases of La$_{2-x}$Sr$_{x}$CuO$_4$ [1–4] and YBa$_2$Cu$_3$O$_{6+x}$ [5–7].

Neutron results indicate that doping with holes by the addition of strontium or oxygen, respectively, produces a strong reduction of the 2D correlation length [8] whereas the magnitude of the Cu magnetic moment is almost unchanged. The

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neutron scattering results on an YBa$_2$Cu$_3$O$_{6+x}$ specimen with a superconducting transition temperature of 50 K are consistent with the existence of highly overdamped spin waves and a very short spin-spin correlation length [9].

$\mu$SR experiments indicate the existence of static magnetic order in superconducting samples close to the metal-insulator transition [10,11], but there are no magnetic correlations on the time scale of the $\mu$SR technique in more heavily doped samples ($T_C > 50$ K in the YBa$_2$Cu$_3$O$_{6+x}$ system and $T_C > 35$ K in La$_{2-x}$Sr$_x$CuO$_4$).

In this paper we present a detailed study of the YBa$_2$Cu$_3$O$_{6+x}$ system at intermediate oxygen concentrations where superconductivity and internal magnetic fields coexist in the same samples. Special emphasis will be given to the spatial distribution of magnetism and superconductivity in these samples.

2. Experimental details

The oxygen-deficient samples were prepared by quenching fully oxygenated materials from elevated temperatures, where the equilibrium oxygen content is reduced, to liquid nitrogen temperature [12]. The $\mu$SR experiments were performed at the low momentum beam at the Paul Scherrer Institut in Switzerland. The low temperature measurements were made at the low temperature facility. This setup utilizes a $^3$He-$^4$He dilution refrigerator and temperatures as low as 30 mK can be obtained. The sample holder was made out of silver in order to avoid signals from muons stopping outside the target. The samples were cooled in zero magnetic field and no magnetic field was applied during the measurement.

3. Results and discussion

Fig. 1 shows $\mu$SR spectra for several YBa$_2$Cu$_3$O$_{6+x}$ samples at temperatures below 1 K in zero applied magnetic field. It should be noted that the samples were prepared by quenching. For these materials the transition region between antiferromagnetic ordering and superconductivity occurs around O$_{6.5}$ and not around O$_{6.4}$ as found for samples prepared in thermal equilibrium. The sample with $x=0.5$ shows a highly damped spin precession indicating the presence of internal magnetic fields. The lowest spectrum in fig. 1 was obtained for a sample with $x=0.7$ with a superconducting transition temperature of 55 K. The muon decay asymmetry in this spectrum was fitted with a single Kubo-Toyabe-function of width $\Delta = 0.2 \mu$s$^{-1}$. This behavior of the asymmetry is characteristic of an interaction of the muon spin with static nuclear magnetic moments.

$$G_c(t) = G^K(t) = \frac{1}{2} + \frac{3}{4}(1 - \Delta^2 t^2) \exp\left[ -\frac{1}{2} \Delta^2 t^2 \right].$$  \hspace{1cm} (1)

The $x=0.57$ and $x=0.67$ samples were superconducting with transition temper-