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NQR AND μSR IN DILUTED TWO-DIMENSIONAL $S = 1/2$ HEISENBERG ANTIFERROMAGNETS*

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^{139}La NQR spectra and relaxation and μSR precessional frequencies in $La_2Cu_{1-x}M_xO_4$ (for M= Zn and Mg) are reported in order to study the effect of spin dilution in the planar quantum Heisenberg antiferromagnet (2DQHAF) La_2CuO_4. The behavior of the spin stiffness $\rho_s(x)$ and of the in-plane correlation length $\xi_{2D}(x,T)$, of the sublattice magnetization and of the Néel temperature, for a dilution approaching the percolation threshold depart sizeably from the ones expected in dilution-like models. In spite of the marked reduction of ρ_s the transition to the ordered state occurs at a temperature, where $\xi_{2D}(x,T_N)$ reaches a value close to the one in undoped 2DQHAF.

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1. Introduction

The behavior of characteristic magnetic properties, such as spin stiffness ρ_s and in-plane correlation length ξ_{2D}, in pure as well as in charge and/or spin disordered two-dimensional quantum Heisenberg antiferromagnets (2DQHAF) has recently attracted a great deal of interest. It has been proved [1–3] that ^{139}La NQR relaxation in $La_2Cu_{1-x}Zn_xO_4$ allows to derive the temperature and doping dependence of $\xi_{2D}(x,T)$. The main conclusions were that for $x \leq 0.1$ ξ_{2D} follows the T-dependence expected in the renormalized classical (RC) regime, with ρ_s and the spin-wave velocity c_{sw} renormalized by quantum fluctuations, with respect to the mean field values. A simple dilution like model was found to account for most of the experimental findings [3]. Of particular interest is the range of strong dilution so

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that the percolation threshold, where no 3D long range order is developed, is approached. In this report we extend the ^{139}La NQR and μSR measurements to La$_2$CuO$_4$ with Mg^{2+} ($S = 0$) for Cu^{2+} ($S = 1/2$) substitution to an extent $x \simeq 0.3$.

2. Experimental results

The ^{139}La NQR spectra and μSR precessional frequencies were used to extract the Néel temperature $T_{\rm N}(x)$ (Fig. 1(a)) and the sublattice magnetization, namely the expectation value $\langle \mu(x, T \to 0) \rangle$ (Fig. 1(b)) (for details on the procedure see Ref. [1]). For low dilution levels one has $(-1/T_{\rm N}(0))(dT_{\rm N}(x)/dx) \simeq 3.2$, as expected for an effective Hamiltonian

$$\mathcal{H} = J_{\rm eff}(x) \sum_{i,j} \vec{S}_i \cdot \vec{S}_j = J(1-x)^2 \sum_{i,j} \vec{S}_i \cdot \vec{S}_j \,. \tag{1}$$

For $x \geq 0.25$ a clear departure occurs, consistent with a percolation threshold at $x = 0.41$. The normalized sublattice magnetization $m = \langle \mu(x,0) \rangle / \langle \mu(0,0) \rangle$ (Fig. 1(b)) is compared to recent evaluations, carried out in the framework of different theoretical models. Only the behavior predicted for m within spin wave theory seems to model the experimental findings. We point out that recent neutron scattering data, up to $x \simeq 0.42$ [4] qualitatively support our observation.

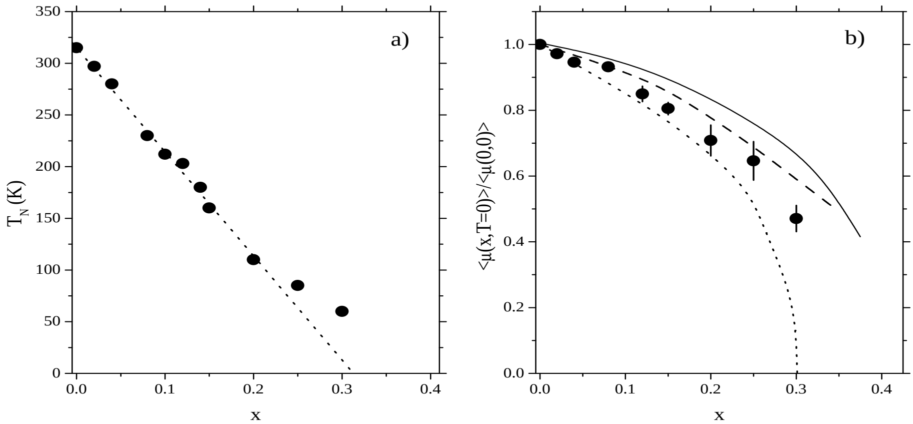

Fig. 1. (a) Néel temperature in La$_2$Cu$_{1-x}$(Mg,Zn)$_x$O$_4$. The dotted line is the behavior expected within the dilution model. (b) Sublattice magnetization as a function of spin dilution. The solid line was derived from quantum Monte Carlo simulations [6], the dashed line from spin-wave theory [7], the dotted line in the framework of an effective quantum non-linear σ model [8].

^{139}La NQR relaxation rate $2W$, for $x = 0.3$, is reported in Fig. 2. From the comparison of the recovery laws for the $2\nu_Q$ and $3\nu_Q$ resonance lines [5] it has been proved that below $T \simeq 140$ K the relaxation process is of magnetic origin, *i.e.* driven by the time-dependence of the hyperfine magnetic field due to Cu^{2+} spins. The phonon contribution to the relaxation mechanism, which yields $2W \propto T^2$, was subtracted to analyze the experimental data.

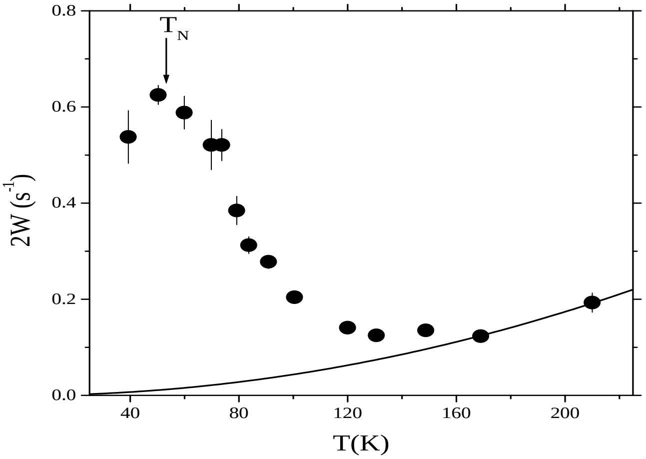

Fig. 2. Temperature dependence of ^{139}La NQR spin-lattice relaxation rate in $La_2Cu_{0.7}Mg_{0.3}O_4$. The solid line shows the phonon contribution to the relaxation.

3. Discussion and conclusions

The relaxation rate $2W$ can be related to $\xi_{2\mathrm{D}}(x,T)$ along lines analogous to the ones already used [2, 3] for pure and lightly doped 2DQHAF. The form factor relating $2W$ to the generalized spin susceptibility was assumed $|A_{\vec{q}}|^2 \simeq 10^6$ Gauss^2. Thus, one can write $2W \simeq 3.3\times 10^{-3}(\xi_{2\mathrm{D}}/a)^z s^{-1}$ (a is the lattice step). The dynamical scaling exponent z was taken $z = 1$, as for undoped or lightly doped 2DQHAF. The behavior of $\xi_{2\mathrm{D}}(x,T)$ (see Fig. 3) is close to the one expected in the RC regime:

$$\xi_{2\mathrm{D}}/a = \frac{\hbar c_{\mathrm{SW}}}{16\pi k_{\mathrm{B}}\rho_{\mathrm{s}}} \mathrm{e}^{\frac{2\pi\rho_{\mathrm{s}}(x)}{T}} \left[1 - 0.5\frac{T}{2\pi\rho_{\mathrm{s}}(x)}\right] . \qquad (2)$$

In Fig. 3 the values $\xi_{2\mathrm{D}}(x,T_{\mathrm{N}}(x))$ estimated from the mean-field argument $(\xi_{2\mathrm{D}}(x,T_{\mathrm{N}}(x))/a)^2 J_{\perp}(1-x)^2 = T_{\mathrm{N}}(x)$ are also reported. It can be concluded that also for high dilution $\xi_{2\mathrm{D}}$ follows rather well Eq. (2), having left $\rho_{\mathrm{s}}(x)$ as an adjustable parameter. The values of $\rho_{\mathrm{s}}(x)$ are reported in Fig. 3. It is noted that in the strongly diluted regime, $x \geq 0.1$,

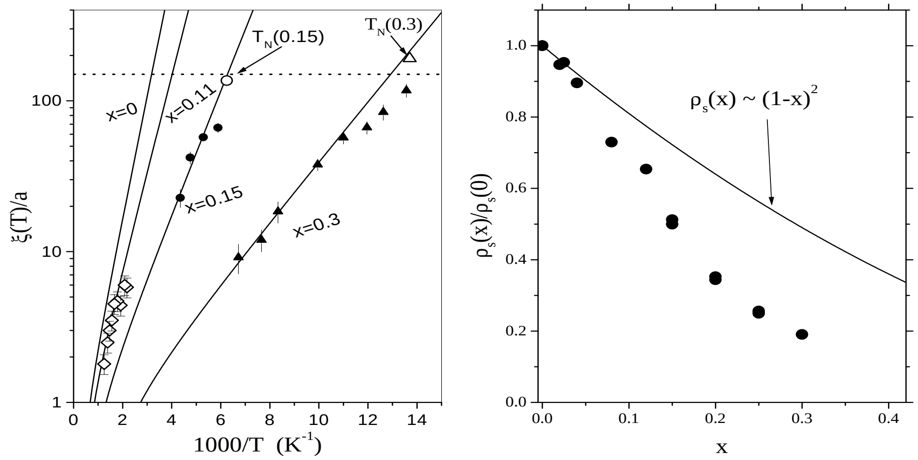

Fig. 3. Left: In-plane correlation length ξ_{2D}/a in $La_2Cu_{1-x}(Mg,Zn)_xO_4$ derived from nuclear relaxation rates (closed symbols) and from T_N values (open symbols). The solid lines show the behavior for ξ_{2D} in the RC regime. The horizontal dotted line shows the value of $\xi_{2D}(x, T \to T_N)$. Right: Spin-stiffness $\rho_s(x)$ in $La_2Cu_{1-x}(Mg,Zn)_xO_4$. The solid line is the behavior expected in the framework of a dilution-like model (see text).

$\rho_s(x)$ departs dramatically from the dilution like model behavior, where $\rho_s(x) = 1.15 J_{\rm eff}(x)/2\pi \propto (1-x)^2$. However, while $\rho_s(x)$ is strongly affected by the spin dilution and $T_N(x)$ is drastically reduced, the transition to the ordered state still occurs when ξ_{2D} reaches a value around 150 lattice steps, as in pure or lightly doped systems.

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