Universal behavior of the magnon gaps in doped quasi-2D antiferromagnets

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Abstract

Within the framework of the anisotropic quantum non-linear σ-model (QNLσM) we calculate doping and temperature dependence of the magnon gaps in a prototypical quasi-2D antiferromagnet $La_{2-x}Sr_xCuO_4$ ($x < 0.02$) and obtain good agreement with experiments. It is shown that the reduction of the magnon gaps relative to their $x = 0$ value weakly depends on the anisotropies of the parent compound. Since the DM gap is highly sensitive to rare-earth element doping, this prediction could be tested on $La_{2-x-y}Eu_ySr_xCuO_4$ (LESCO) and $La_{2-x-y}Nd_ySr_xCuO_4$ (LNSCO).

Motivation

In lightly doped $La_{2-x}Sr_xCuO_4$ (LSCO):

- Dzyaloshinskii-Moriya (DM) and XY anisotropies generate small magnon gaps ($\sim 2\%$ of the AF exchange constant) [1].
- The gaps decrease with doping **much faster than is expected** from reduction of the underlying anisotropies [2, 3].

Questions:

- What is the mechanism responsible?
- Is the magnon gap dependence on doping sensitive to the details of the parent compound?

The model

Anisotropic non-linear σ-model (NLσM) coupled to the dipole fields representing holes:

$$\mathcal{L}_s = \frac{\rho_s}{2c}[(\partial_0 \mathbf{n})^2 + (\partial_i \mathbf{n})^2 + (\frac{\omega_0^\alpha}{c})^2 (n^\alpha)^2], \tag{1}$$

$$\mathcal{L}_{s-\text{dipole}} = \frac{g_d}{c} \mathbf{P}_i \cdot (\mathbf{n} \times \partial_i \mathbf{n}), \tag{2}$$

$$\mathcal{L}_{\text{dipole}} = \frac{1}{2\kappa c} \mathbf{P}_i G_d^{-1} \mathbf{P}_i. \tag{3}$$

$\mathbf{n}^2 = 1$ – staggered magnetization, $G_d(i\omega_n, \mathbf{q}) = \frac{Dq^2}{Dq^2 + |\omega_n|}$ – dipole field propagator, ω_0^α – bare magnon gaps, ρ_s – spin stiffness, c – spin-wave velocity, g_d – spin-dipole coupling constant.

Methods

- Dipole fields can be integrated out $\Rightarrow$ **effective spin interaction** term:

$$\mathcal{L}_{\text{int}} = -\frac{g_d^2 \kappa}{4c} n^k \overleftrightarrow{\partial}_i n^l G_d n^k \overleftrightarrow{\partial}_i n^l \xrightarrow{D \gg 1} -[g_d^2 \kappa/(2c)] \cdot (\partial_i \mathbf{n})^2. \tag{4}$$

- In the **diffusive limit** ($D \to \infty$) one gets pure spin stiffness and spin-wave velocity renormalization ($\rho_s \to \rho_s - g_d^2 \kappa$, $\rho_s/c^2 = \text{const.}$).
- We derive the **effective action** for the QNLσM in the diffusive limit ($D \gg 1$) to the one-loop order:

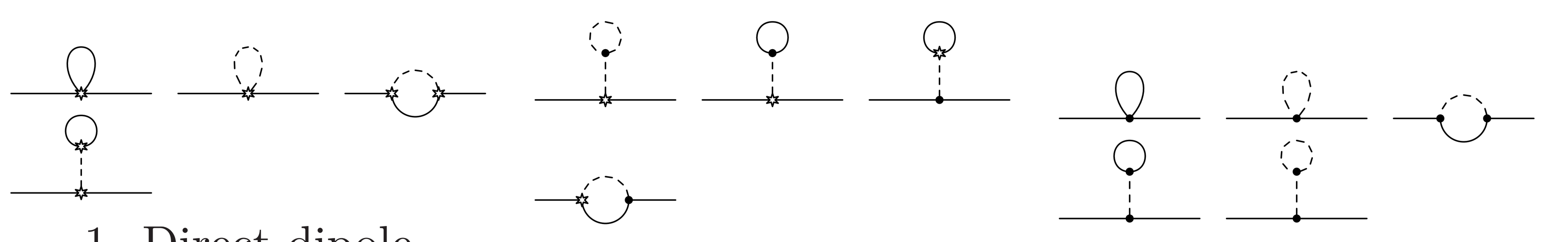
$$S_{\text{eff}} \approx \sum_\gamma \frac{\rho_R^\gamma}{2c} \int_0^{c/T} dx_0 \int d^2x [(\partial_\mu n_0^\gamma)^2 + (\frac{\omega_R^\gamma}{c})^2 (n_0^\gamma)^2], \tag{5}$$

where

$$\rho_R^\alpha = \rho_s [1 - \frac{c}{\rho_s} \sum_\gamma \int d\tilde{\mathbf{q}} G_{0\pi}^\gamma(\tilde{\mathbf{q}}) + \frac{c}{\rho_s} \int d\tilde{\mathbf{q}} G_{0\pi}^\alpha(\tilde{\mathbf{q}})], \tag{6}$$

$$\omega_R^\alpha = \omega_0^\alpha [1 - \frac{c}{\rho_s} \int d\tilde{\mathbf{q}} G_{0\pi}^\alpha(\tilde{\mathbf{q}})]. \tag{7}$$

- **Alternative approach** – linear σ-model (can be easily used away from the diffusive limit). The results obtained within NLσM are confirmed.



1. Direct dipole channel 2. Mixed spin-dipole channel 3. Spin channel

Results

- The dependence of ρ_s and c on doping is obtained from the empirical scaling law for staggered magnetization (cf. Ref. [4]):

$$\begin{cases} \frac{M^\dagger(x)}{M^\dagger(0)} \sim (1 - \frac{x}{x_c})^\mu, \text{ where } x_c = 0.023, \mu = 0.236 \\ (M^\dagger)^2 \sim 1 - \frac{g(x)}{g_c} \end{cases} \tag{8}$$

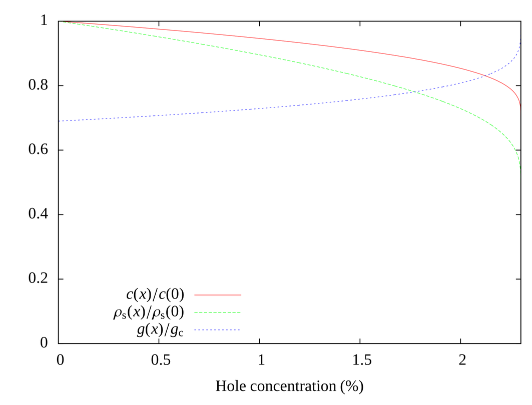


Fig. 1. Doping dependence of the normalized spin stiffness, spin-wave velocity and the QNLσM coupling constant obtained from Eq. (8).

- Doping and temperature dependence of the magnon gaps in LSCO:

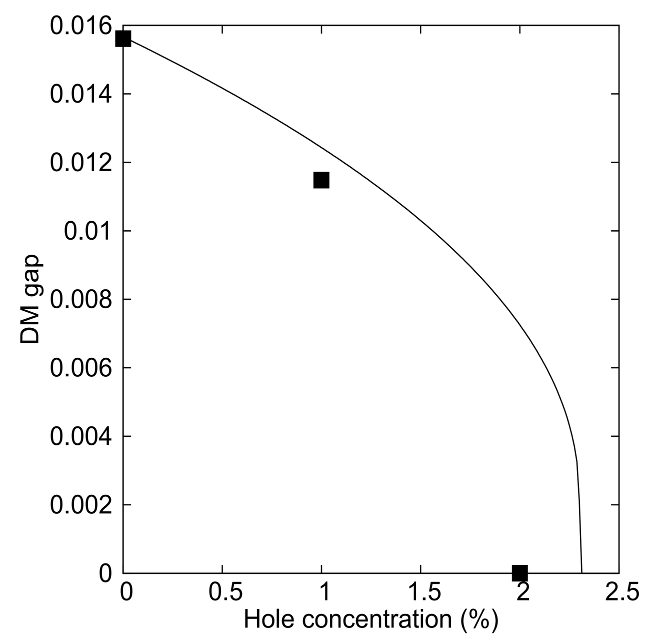


Fig. 2. DM gap vs doping for LSCO (in the units of J). The solid line is the theoretical curve for 10K. Solid squares are the experimental data of Ref. [2]

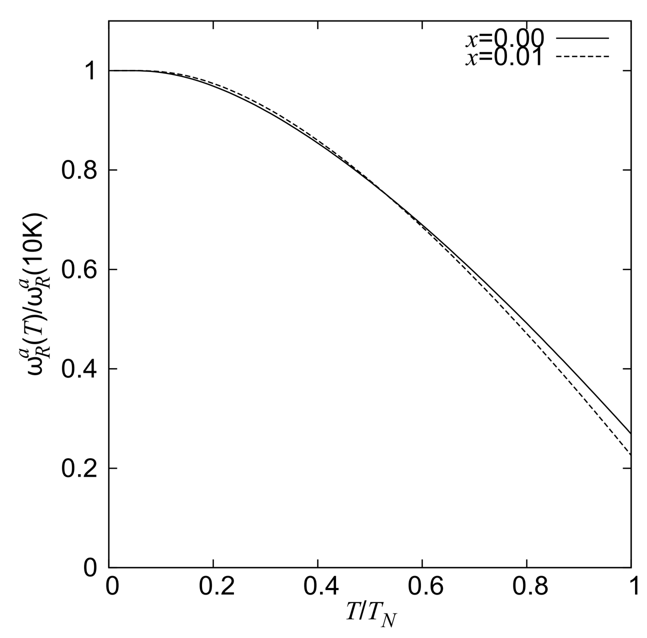


Fig. 3. Normalized DM gap ω_R^α vs temperature for LSCO ($x = 0$ and $x = 0.01$). The solid and dashed lines are the theoretical curves. The Néel temperature $T_N(x)$ is taken from Ref. [4].

- **Universal doping dependence** of the magnon gaps is predicted for various La-based cuprates:

$La_{2-x}Sr_xCuO_4$			$La_{1.65-x}Nd_{0.35}Sr_xCuO_4$		
x	experiment	this work	x	experiment	this work
0.00	2.1 meV	2.1 meV	0.00	4.5 meV	4.5 meV
0.01	1.55 meV	1.66 meV	0.01	?	3.68 meV
21% reduction predicted			18% reduction predicted		

Table 1. Comparison of the in-plane gaps in LSCO and LNSCO with NLσM predictions for different Sr doping levels. The experimental values are taken from Refs. [2, 4, 5].

Summary

- **The dependence of the magnon gaps on doping has been discussed** within the framework of the non-linear σ-model.
- **Good agreement** with available experimental data is obtained.
- The relative magnon gap reduction with doping **is predicted to be insensitive to the anisotropies** of the parent compound.

References

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