University of Groningen
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Modelling Dynamical Fluorescent Micro Thermal Imaging of the Heat Diffusion in the $La_5Ca_9Cu_{24}O_{41}$ Spin Ladder Compound.

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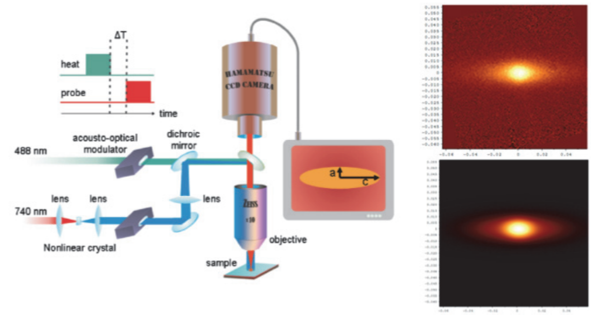
Abstract

The dynamical fluorescent micro-thermal imaging (FMI) experiment [1] has been used to investigate the phonon-magnon interaction in the 1D Heisenberg antiferromagnet La5Ca9Cu24O41. This material shows highly anisotropic heat conductivity due to the efficient magnetic heat transport along the spin ladders in the compound [2]. To extract information on the phonon-magnon interaction we modelled the dynamic heat transport experiment using a two temperature model approach [3, 4] and taking both the crystal as well as the PMMA/EuTTA fluorescent heat imaging layer into account. The simulations are carried out by the finite element method using COMSOL Multiphysics Heat Transfer Module [5]. The results of the numerical calculations are crucial to the data analysis of the experimental studies.

Fluorescent micro-thermal imaging (FMI)



Modelling of the multicomponent heat transport

Governing equations . 1T model approach: $\mathbf{c_{tot}\partial_t}T = \mathbf{\nabla(k_{tot}\nabla}T\mathbf{) + Q}$

2T model approach:
$$\begin{cases}\mathbf{c_l\partial_t T_l = \nabla(k_l\nabla T_l) - g(T_l - T_m) + Q} \\ \mathbf{c_m\partial_t T_m = \nabla(k_m\nabla T_m) - g(T_m - T_l)}\end{cases}$$

where cl, kl, Tl and cm, km, Tm are the specific heat, thermal conductivity and temperature of the phonon and magnon systems, respectively, and g is the coupling constant between the magnons and the phonons :

$$g = \frac{c_m c_l}{c_m + c_l}\frac{1}{\tau_{ml}}$$

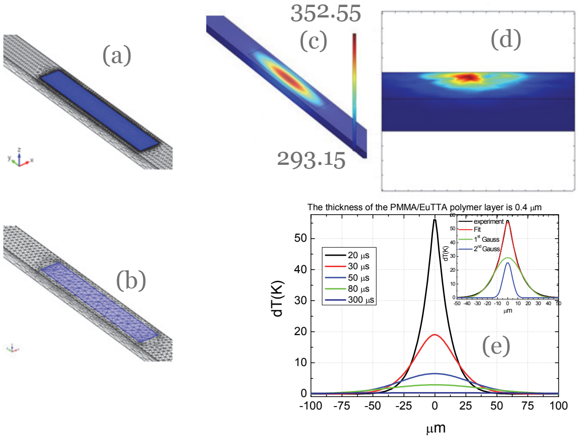
where τ_{mp} is the phonon-magnon thermalization time.

Dimensions of the sample:
20 µm x 2000 µm x 60 µm
(finer mesh - 9µm x 300µm x 40µm)

The heating laser pulse is represented as a Gaussian function in space with σ = 2.3 µm and a block function in time with duration of 20µs. The energy of the laser pulse is taken as E=0.02µJ per pulse, corresponding to the experimental conditions.

Quantity	*$La_5Ca_9Cu_{24}O_{41}$*	PMMA / EuTTA layer	Dimensions
k_l	1^*	1.19^*	$WK^{-1}m^{-1}$
k_m	34.5^*	-	$WK^{-1}m^{-1}$
c_l	27.42[4]	1466	$JK^{-1}kg$
c_m	522.913[4]	-	$JK^{-1}kg$
ρ	5469.36	1190	$kg\ m^{-3}$
τ_{ml}	4e-4[4]	-	sec

Table 1: 2T Model parameters used in the numerical simulations.



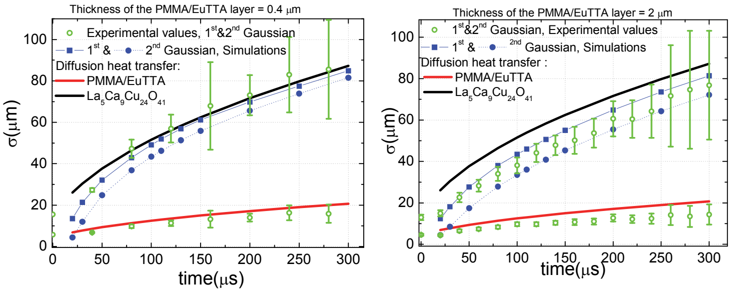
The space mesh of the geometry of the 1T (a) and the 2T (b) models, blue areas corresponds to the finer mesh around the hot spot.

Example of the data analysis. (c) 3D temperature distribution of the sample corresponding to the anisotropic heat transport along the spin ladders for 1T model approach.(d) 2D temperature distribution of the XY plane cross section of the sample. (e) 1D temperature distribution corresponding to the average of 2D temperature distribution of the polymer layer along the z axis for five different time delays. Insert: Fitting of the 1D temperature distribution by two Gaussian functions:

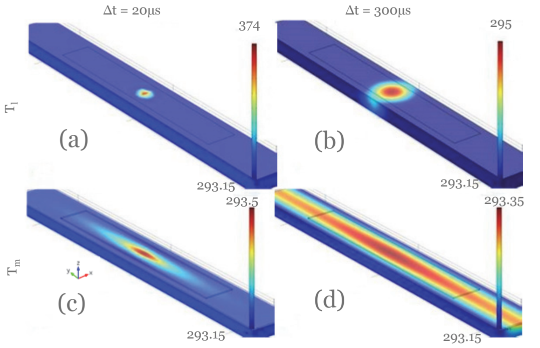
$$F(x) = H_1\ e^{-0.5\left(\frac{x-x_{01}}{\sigma_1}\right)^2} + H_2\ e^{-0.5\left(\frac{x-x_{02}}{\sigma_2}\right)^2}$$

Where widths σ1 and σ2 corresponds to the effective thermal diffusivities of the sample and the polymer layer, respectively; and amplitudes, H1 and H2, gives the relative importance of the two transport channels.

Simulation Results



1T model simulations results. Blue lines: the time dependence of widths of the 1st and 2nd Gaussians extracted from the 2D temperature profile of the polymer layer with two different thicknesses – 0.4µm (a) and 2µm (b), along the spin ladders. Red and black lines: the simulation and experimental results are collated also to the diffusion functions – √(2Dt+σ$_o$²), where t is time, D is diffusivity of the La5Ca9Cu24O41 and PMMA/EuTTA and σ$_o$ is the width of the laser pulse, as used in the model. Green lines: time dependence of the 1st and 2nd Gaussians extracted from the experimental data with the corresponding confidence intervals.



2T model simulations results. (a, b) Phonon 3D temperature distribution directly after applying the heat laser pulse and at the last calculated time delay (Δt = 300µs), respectively, for the 2T model approach. (c,d) Magnon 3D temperature distribution for the same time delays for the 2T model approach.

Conclusions.

Present study shows a strong correlation between the thickness of the polymer layer and observed thermal conductivity of the sample for both used approaches. This result can be used for the data analysis of the dynamical-FMI experimental studies in order to exclude the heat transport in polymer layer from the experimental results by the fitting the temperature profiles with sum of two Gaussian function. The 2T approach shows not efficient phonon-magnon coupling, as can be seen from a comparison with experimental data. The applying of the 2Temperature model is required further modelling.

References:

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Acknowledgements:

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