Title
Determination of the spin-flip time in ferromagnetic SrRuO3 from time-resolved Kerr measurements

Permalink
https://escholarship.org/uc/item/9w5583d4

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Publication Date
2010-09-30

Peer reviewed
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FIG. 1. Derivative of the change in Kerr rotation as a function of time delay following pulsed photoexcitation, for $T < 85$ K. This motion is described by the Landau-Lifshitz-Gilbert equation with the frequency of oscillation proportional to the strength of the magnetocrystalline anisotropy field, and the damping described by dimensionless phenomenological parameter, $\alpha$. The motion appears as a decaying oscillation to TRMOKE. The orientation of the anisotropy field, closer to in-plane with the sample surface in SRO/STO(111) than in SRO/STO(001), makes these oscillations more prominent when observed with the polar Kerr geometry compared to previous measurements.

Attempting to model the time derivative of $\Delta \Theta_K$ with a damped cosine reveals that it cannot be fit by such a function for $t < 2$ ps. The feature at short times in Fig. 1 contains higher frequency components, whereas the oscillations which become clear after 2 ps are at a single frequency. A comparison of the amplitude of the first peak (at $t \sim 1.5$ ps) with the amplitude of the subsequent oscillations (defined as the difference between $d \Delta \Theta_K/dt$ at the peak at $\sim 3.5$ ps and the dip at $\sim 5.5$ ps), is shown as a function of temperature in Fig. 2. The constant offset between the two amplitudes indicates that $d \Delta \Theta_K/dt$ is comprised of a superposition of a temperature independent, short-lived component with the longer lived damped oscillations.

Fitting the oscillatory portion of the signal to a damped cosine, the temperature dependencies of the amplitude, frequency, and damping parameter are found, as shown in Fig. 3. Comparing these parameters for SRO/STO(111) to previously published work on SRO/STO(001), the frequency is found to be somewhat smaller and to change more with temperature. Of particular interest is $\alpha$, which is also smaller in this orientation of SRO, consistent with the more pronounced FMR oscillations. Strikingly, in both orientations there is a dip in $\alpha$ around 45K, which is relatively stronger in SRO/STO(111). This further strengthens the link between $\alpha$ and the anomalous hall conductivity, speculated in that paper, through near degeneracies in the band structure.

IV.2: Experimental Results: High Temperature

FIG. 2. Comparing amplitudes of the short time feature and the ferromagnetic resonance oscillations.

By taking the time derivative of $\Delta \Theta_K$, the FMR oscillations can be followed until they disappear at elevated temperatures, at which point it becomes simpler to look at $\Delta \Theta_K$ than its time derivative. Fig. 4 shows $\Delta \Theta_K$ as a function of time for the first 38 ps after excitation by the pump laser, for temperatures between 120K and 165K. A property of a second order phase transitions is that the derivative of the order parameter diverges near the transition temperature. The peak in magnitude of $\Delta \Theta_K$ in figure 4, shown in figure 5, can be understood as the result of the derivative of magnetization with respect to temperature becoming steeper near the Curie temperature. A strong temperature dependence of the demagnetization time, $\tau_M$, is seen, with $\tau_M$ significantly enhanced near 150K, consistent with previous reports on SRO.

$\Delta \Theta_K(t)$ in Fig. 4, normalized by the largest value of $\Delta \Theta_K(t)$ in the first 38 ps, can be fit with the following function:

$$
\Delta \Theta_K(t) = \begin{cases} 
\Delta \Theta_{\text{max}}(t=0) & \text{for } t < 0 \\
C - Ae^{-t/\tau_M} & \text{for } t > 0
\end{cases}
$$

for $t < 0$ $\Delta \Theta_K(t) = \Delta \Theta_{\text{max}}(t=0)$ for $t > 0$ $\Delta \Theta_K(t) = C - Ae^{-t/\tau_M}$

where the decay time is $\tau_M$. The resulting $\tau_M$ is plotted as a function of temperature in Fig. 6. Notably, $\tau_M$ increases by a factor of 10 from 135K to 150K. Taking the fit value of $T_c = 148.8$K, as will be discussed later, $\tau_M$ is plotted log-log as function of reduced temperature, $T_R = (T_c - T)/T_c$. The result looks approximately linear, indicating a power law dependence of $\tau_M$ on the reduced temperature.

V: Discussion of Results: Efforts to explain demagnetization have been largely phenomenological thus far, understandably, given the daunting challenge of a full microscopic model. Beaurepaire et al. introduced the three temperature model (3TM) to describe demagnetization resulting from the interactions of the electron, phonon, and spin baths. In 3TM the dynamics are determined...
FIG. 3. Temperature dependence of (a) Amplitude of oscillations, (b) FMR frequency, and, (c) damping parameter.

FIG. 4. Change in Kerr rotation as a function of time delay following pulsed photoexcitation, for $120 < T < 165$ K.

FIG. 5. Magnitude of change in Kerr rotation at 38ps as a function of temperature.

FIG. 6. Demagnetization time at high temperature by the specific heats of each bath as well as the coupling constants between them. Demagnetization can generally be described with the appropriate choice of coupling constants, providing a guide into the microscopic mechanism. Koopmans et al. also offer a phenomenological description of demagnetization considering three baths, but one that follows spin in addition to heat. Spin is treated as a two state system with energy levels separated by an exchange gap and Fermi's golden rule is used to relate demagnetization to electron scattering which flips a spin. Equations for coupling constants are derived based on parameters such as the density of states of electrons, phonons, and spins, the electron-phonon scattering rate, and the probability of spin flip at a scattering event.

In the following we attempt to understand the behavior of the demagnetization time near $T_c$ with an approach based on the two spin state model. A general relationship between the laser-induced $\tau_M$ and the spin flip time, $\tau_{sf}$, can be derived near the transition temperature based on the concept of detailed balance.

In equilibrium, the ratio of the probability of...
The demagnetization time can be written as:

\[
\dot{S} = \frac{\beta N_{total}}{kT} \frac{N_{maj}}{N_{maj} - N_{min}} \Delta T_{ex}
\]

where \( \Delta T_{ex} \) is the initial change in the time derivative of the electron temperature, once electrons, phonons, and spins have come into thermal equilibrium with each other.

The rate of change of \( S \) with respect to temperature, \( \frac{dS}{dT} \), can be written:

\[
\frac{dS}{dT} \approx \frac{\Delta T_{eq}}{kT_{eq}} \frac{N_{maj} - N_{min}}{N_{maj} - N_{min}}
\]

where \( T_{eq} \) is the equilibrium temperature. A fit of \( T_{eq} \) near the Curie temperature is found for the mean field value of \( T_{eq} \).

Additionally, the critical exponent found is independent of laser power. In the last equation

\[
\frac{dS}{dT} \approx \frac{\Delta T_{eq}}{kT_{eq}} \frac{N_{maj} - N_{min}}{N_{maj} - N_{min}}
\]

Note that detailed balance suggests that the demagnetization time scales are linked to divergent length scales, but here excitations should not be considered. In general, divergent time scales are revealed near the transition temperature, and \( S \) scales with \( \Delta T_{ex} \) as typically considered.

It should also be noted that the current situation, where the sample has been excited by a laser, is distinct from critical behavior as typically considered. In general, divergent time scales are revealed near the transition temperature, and \( S \) scales with \( \Delta T_{ex} \) as typically considered.

Near the Curie temperature, \( \Delta T_{ex} \) is found for the SRO10, in Fig. 8.

\[
\Delta T_{ex} \sim 148.8K
\]

Therefore \( \tau \) is predicted to scale as

\[
\tau \sim \beta \tau_{eq}
\]

where \( \beta \) is the critical exponent found is independent of laser power. In the last equation

\[
\tau \sim \beta \tau_{eq}
\]

Additionally, the critical exponent found is independent of laser power. In the last equation
FIG. 8. Spin flip time at high temperature

Previous reports of conductivity in SRO give a scattering time of $\sim 20$ fs near the transition temperature. A comparison of the spin flip time with the scattering time implies a probability of 0.1 that a scattering event results in a spin flip.

Though electron-phonon interactions are the most commonly considered source of demagnetization, as mentioned previously, Eliot Yafet-like electron-electron coulomb scattering can also result in demagnetization. This is especially true for materials with strong spin orbit coupling, such as SRO. Additionally in SRO the interaction with the crystal field means that total spin is not conserved, so every electron interaction can perturb the spin state.

Having found a relationship between the demagnetization time and the spin flip time, we would like to explore the relationship between these parameters and the damping parameter, $\alpha$. Intuitively, the damping parameter should be proportional to the spin flip scattering rate, or inversely proportional to the spin flip scattering time:

$$\alpha \sim \frac{1}{\tau_{sf}}$$

Elliot-Yafet type scattering dissipates energy from motion described by the LLG equation by disrupting the coherent, collective precession of spins. Spins that have had their angular momentum changed through electron collisions must be pulled back into the precession through the exchange interaction, representing a transfer of energy away from the precessional motion. These collision-mediated spin-orbit coupling effects are thought to be the primary source of Gilbert-type damping in ferromagnets.

Combining the spin flip time and the damping parameter with Planck's constant reveals an energy scale, $E$, given by

$$\frac{1}{\alpha} \sim \frac{\hbar}{\tau_{sf}}$$

Noting that the values for $\alpha$ and $\tau_{sf}$ found in figures 3 and 7, respectively, are approximately constant as a function of temperature, this energy scale for SRO is $\sim 7$ meV. The fundamental energy scales applicable to the magnetic system in SRO are the Fermi energy, the exchange energy, and the critical temperature, the last two of which are interdependent. The Fermi energy is orders of magnitude larger than 7 meV, but the energy associated with the critical temperature, $k_B T_c \sim 13$ meV, is of the same order. This suggests an underlying connection between the critical temperature (and thus the exchange energy), Gilbert damping, and spin flip scattering.

A relationship similar to equation (12) has been found previously between $\tau_M$ (rather than $\tau_{sf}$) and $\alpha$ by Koopmans et al. at low temperature:

$$\tau_M = \frac{4}{\hbar} k_B T_c \frac{1}{\alpha}$$

Applying this equation to SRO at 5K yields $\tau_M \sim 30$ fs, which is unphysical since it is below the total scattering rate of $\sim 100$ fs at low temperature. Whether the fundamental relationship is between transition temperature and the demagnetization time or the spin-flip scattering time remains a question for a microscopic model to resolve.

ACKNOWLEDGMENTS

This research is supported by the US Department of Energy, Office of Science under contract number DE-AC02-05CH1123.
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