Micromagnetic simulations of metastable states in circular magnetic dots

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Magnetic confinement in nanomagnets leads to a variety of topological anomalies which can be decomposed into two topologically different basic types: domain walls and vortices. The simplest ground states of the circular magnetic dot are the state with uniform magnetization (present in thin dots or in any dots in a high magnetic field) and magnetic vortex state with single vortex with about 10 nm vortex core situated in the dot center. Transition from the uniform to the vortex type ground states, when controlled by the magnetic field, involves two well defined intermediate metastable states: namely the so called S-type and double vortex states [1,2]. Here, by using micromagnetic simulations, we present the first detailed study of transition between different metastable states of circular magnetic dots. The simulations were performed using an extension [3] on the original OOMMF code [4] that augments to the LLG equation a highly irregular fluctuating field, so the resulting equation is a stochastic differential equation of the Langevin type [5]. The micromagnetic simulations were carried out for a circular Py dot having a thickness of 25 nm and a diameter of 1035nm.

We first saturated the dot at 1000 Oe, subsequently we released this field in one step and tracked the energy and total magnetization of the system every ns and took a snapshot of the local magnetization every 10ns, see figure 1. To break the deterministic characteristic of OOMMF, we used a different set of random fluctuation for each run that we made as can be seen in figure 2. By using this method we could identify different energy steps in the relaxation from saturation to zero field as can be seen in figure 1. These steps correlate with different metastable (MS) states. The 4 typical topologies that arise are first the saturated state, then the MS_1 S-State, the MS_2 double-vortex (DV) state and finally the one- vortex ground state. Typically a dot needed about 20~40ns to reach the one-vortex state. Although in some runs this state was never reached and the system remained in a MS state for at least the duration of our simulations (~ 200ns). For both the MS_1 S-state and the MS_2 DV-state, there were runs were this state remained stable in this period. For the MS S-state these stable so called ‘hard’ states are characterized by a more symmetric magnetization than their ‘soft’ unstable counterparts, see figure 1 on the right.

Also we saw instances where the double vortex state remained the stable state at zero field. This is in accordance with [1], where the authors reported the formation of double vortices during the reversal of the magnetization for dots of large diameter (1um). They found experimentally that the double vortex state appears in about 20% of the cases during in-plane reversal of magnetism for Co dots. We propose that that the DV-state always appeared but that just in 20% of the cases it was stable long enough to be measured. In our simulations we saw a range of distribution of core polarities P and positions of the two cores, as can be expected from symmetry arguments. The central part of a DV-vortex is however always diagonally oriented, with the Mx component anti-parallel to the history field.
Our findings open perspectives of investigation of both static and dynamic properties of different metastable states in nanomagnets.

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References:

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Figures:

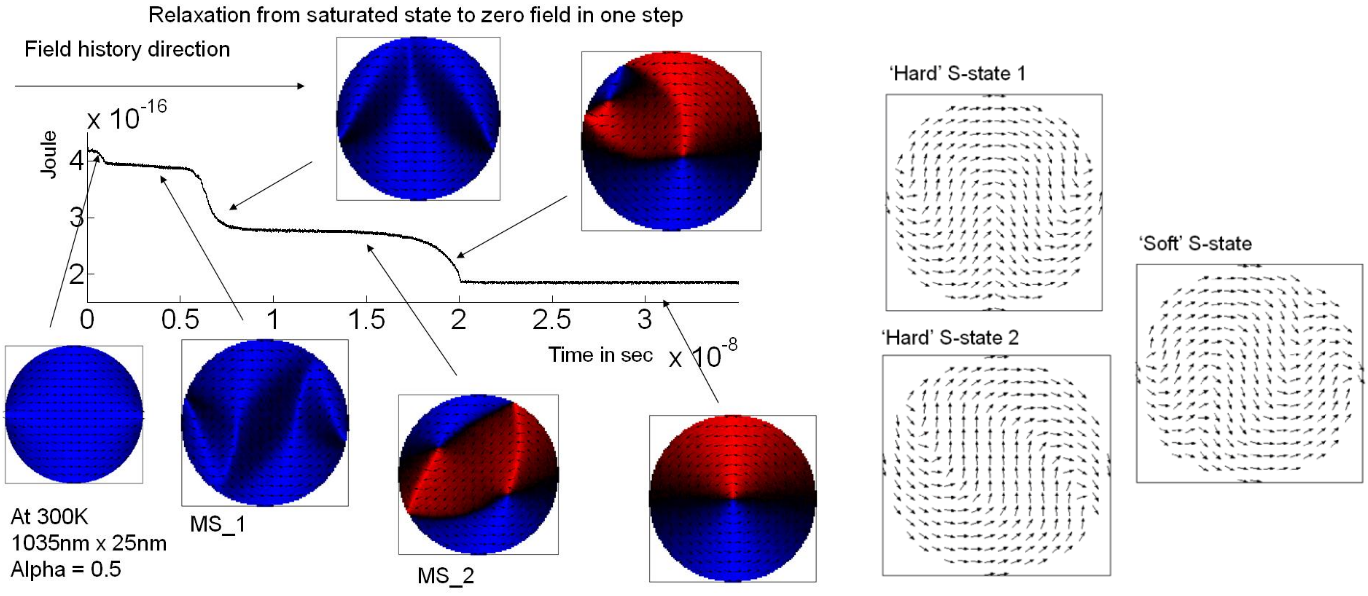

Fig 1: Left: Total energy as a function of time after the 1000Oe saturation field is turned up abruptly. Three different levels can clearly be distinguished. The insets show the snapshots of the magnetization at the indicated time, with a colour coding for Mx. MS_1 and MS_2 signify the MS S-state and the MS DV-state respectively. Right: Several MS S-states. The stable hard states and a unstable soft state. (dot: 1035x25nm)

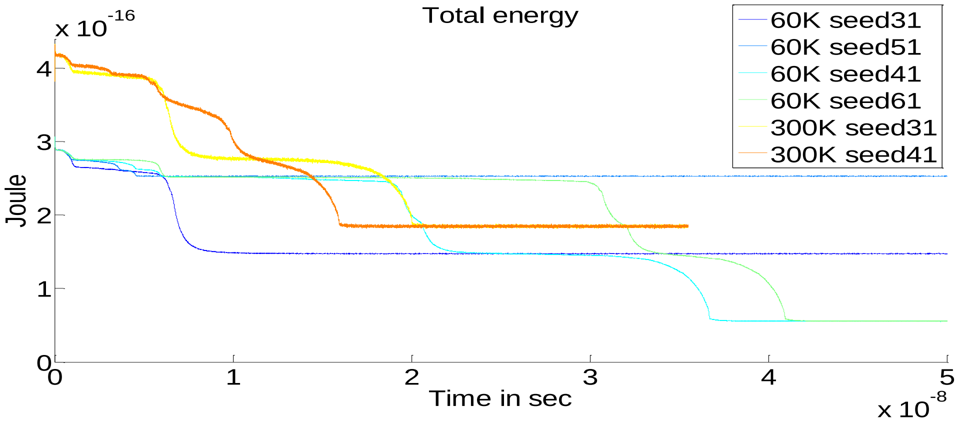

Fig 2: Total energy as function of time for several different runs with different random fluctuations (seeds) at 60K and 300K. For 60K two runs don´t lead to the one-vortex ground state but remain in either an hard S-state or MS DV-state.