NUMERICAL SIMULATION OF ANTIFERROMAGNETICALLY COUPLED NANOMAGNETS

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ABSTRACT

We study the dynamical behaviour of a system that consists of three identical elongated nanomagnets. The magnets are coupled antiferromagnetically and subjected to periodically changing external magnetic field. The numerical simulation of the system reveals the qualitatively different kinds of hysteresis loops.

THE STUDIED SYSTEM

In the last few years, significant attention has been concentrated on understanding the physical properties, and especially on the hysteresis, of magnetic nanosized particles [1, 2]. Both theoretical [3] and experimental [4, 5] studies indicate that the internal magnetic structure of sufficiently small particles can be regarded as a ferromagnetic monodomain. Therefore we identify each particle with one magnetic moment $\vec{m}_i$, where i= 1,…,N, where N is the total number of particles (N=3 in this work). We use the following Hamiltonian:

$$E = -J\sum_{i=1}^{N-1}\vec{m}_i \cdot \vec{m}_{i+1} + \frac{a}{2}\sum_{i=1}^{N}\left(m_y\right)^2 + \frac{b}{2}\sum_{i=1}^{N}\left(m_z\right)^2 - \sum_{i=1}^{N}\vec{H}\cdot\vec{m}_i$$

where J is the usual exchange-energy term, a=40 and b=100 are the anisotropy coefficients originating from shape-anisotropy. As a and b are positive, there is an effective easy x-axis and hard z-axis anisotropy at the same time. H is the applied external magnetic field, which is homogeneous and has only an x-component in this paper. When the nanomagnets are in close proximity the exchange coupling dominates the form of the coupling, coming from the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction, which can be ferromagnetic (J>0) or antiferromagnetic (J<0). We note that there is no explicit dipole-dipole coupling in this Hamiltonian. One can consider it included into the exchange-coupling term which therefore can be regarded as an effective coupling.
In order to derive the equations of motion we use the well-known Landau-Lifshitz-Gilbert equations [6], in which the first term on the right hand side causes only precession around the energetically favoured axis while the second term is the dissipation:

$$\frac{\partial \vec{m}_i}{\partial t} = -\gamma\vec{m}_i \times \vec{H}_{eff} - g\vec{m}_i \times \vec{m}_i \times \vec{H}_{eff}$$

where γ and g are constants with values γ=1 and g=0.1 in this work. The effective field acting on the i-th particle is

$$\vec{H}_{eff} = -\frac{dE}{d\vec{m}_i}$$

To investigate the hysteresis and the magnetization reversal we apply a periodic magnetic field:

$$H_x(t) = H \cdot \sin(2\pi \cdot f \cdot t)\ ,\ H_y(t) = 0\ ,\ H_z(t) = 0$$

where H=200 and f=10^{-5}/numerical timestep.

In our previous paper [7] we have given a full description of the behaviour of N=2 magnetic particles, both analytically and numerically. In this work we continue the numerical investigation for N=3 particles, while the analytical results will be published elsewhere [8]. For the numerical solution of the dynamical differential equation-system the Runge-Kutta method has been used with adaptive stepsize control, written in programming language C.

THE RESULTS OF THE SIMULATION

For ferromagnetic or weak antiferromagnetic coupling the hysteresis loops are identical to the simple case of one particle, and looks like a square. During the very short period of the magnetization-reversal the moments may move into the opposite direction and become antiparallel, but this does not affect the shape of the square hysteresis loop.

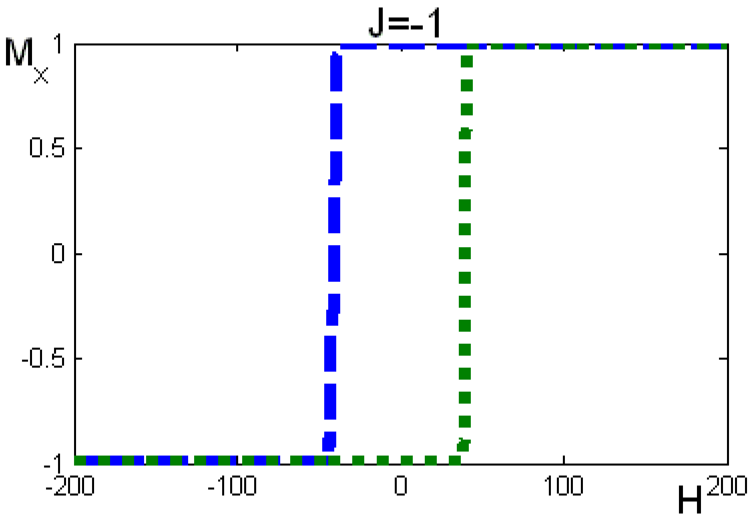

FIG.1. Square hysteresis loop for J=-1.

This simple hysteresis loop can be seen in Fig. 1. In the horizontal axis, H is the magnitude of the external field. In the vertical axis $M_X = \sum_{i=1}^{N} m_{i,x}$ is the x component of the total magnetization of the system, normalized by one. The data for decreasing field are denoted by blue dashed line while for increasing field we use green dotted line.

For non-negligible AF coupling, the shape of the hysteresis loop is not so simple. If we decrease the field from saturation, the system suddenly jumps to an antiferromagnetic state in which the 1. and the 3. moments has the direction x to minimize the Zeeman energy while the 2. moment points to the –x direction to minimize the coupling term. It means that the system performs two large Barkhausen jumps from positive to negative saturation. We note that in Fig. 1. and 2. the remanence is equal to the saturation magnetization, but for stronger and stronger coupling the first jump occurs sooner and sooner, thus the remanence becomes only 33.3% of the saturation magnetization.

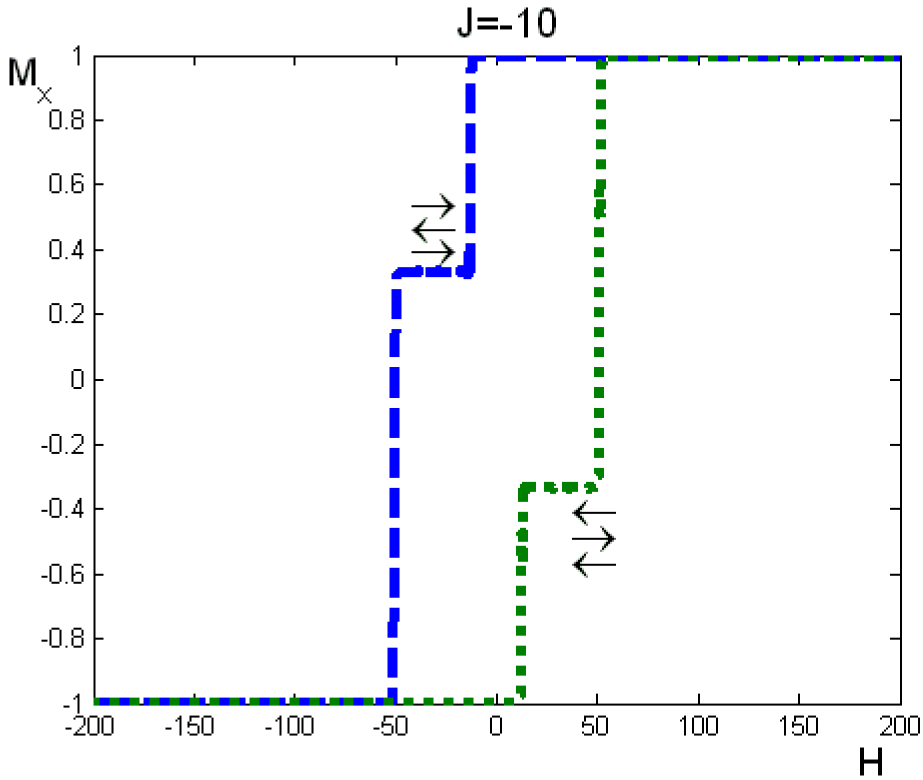

FIG.2. Hysteresis loop for J=-10.

If the coupling reaches about J=-35.56, the shape of the hysteresis loop changes suddenly. Instead of two Barkhausen jumps now we can observe three equal jumps. Now from the M_x=1/3 antiferromagnetic state the system does not jump to the M_x=-1 saturated state directly, but only to the other M_x=1/3 antiferromagnetic state and only later (stronger negative field) to the M_x=-1 state. During the first AF-AF transition, all the 3 moments make a 180^o reversal. The simulation reveals that this is not a trivial process, since one can see first an “overshoot”, then some dynamic oscillation around the finite direction of the moments. We can say dynamic, because the static analysis cannot explain this precessional motion and it strongly depends on the damping and to a lesser extent on the frequency of the field.
Roughly at the same value of coupling a new, so called scissored state appears gradually. When the system leaves saturation for decreasing field, the moments first start to deviate slowly into opposite directions in order to minimize the exchange energy. However, the angles of the deviation is not the same for the moments, as they were for N=2 particles.

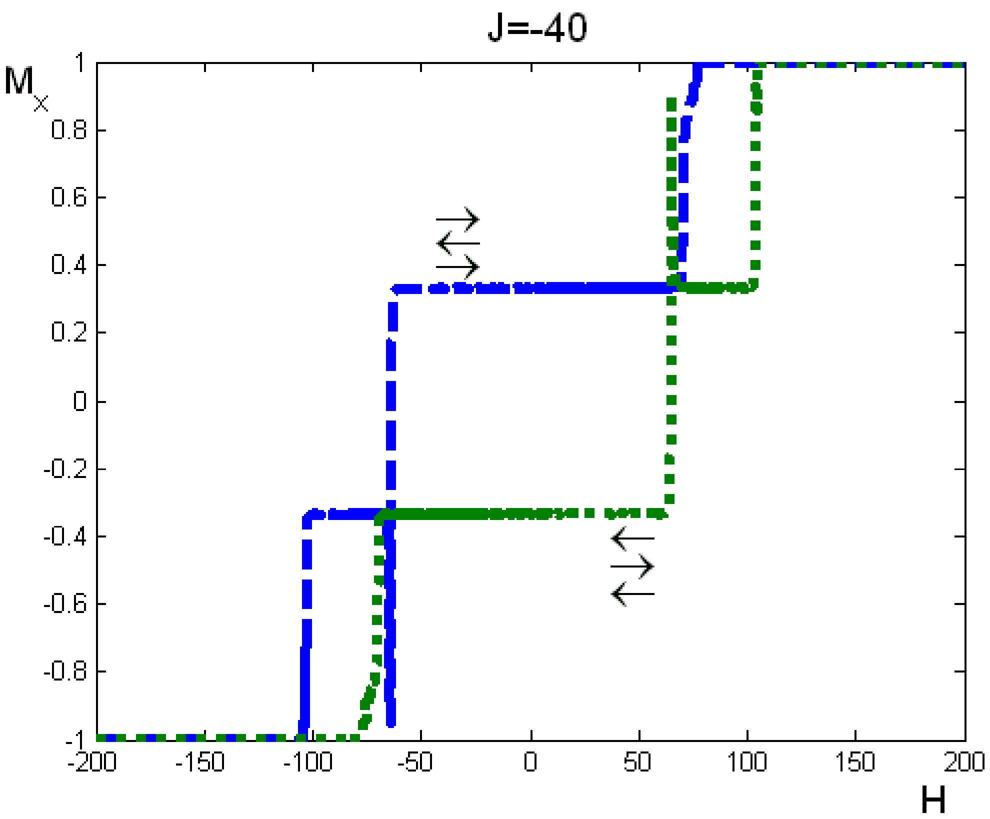

FIG.3. Hysteresis loop for J=-40

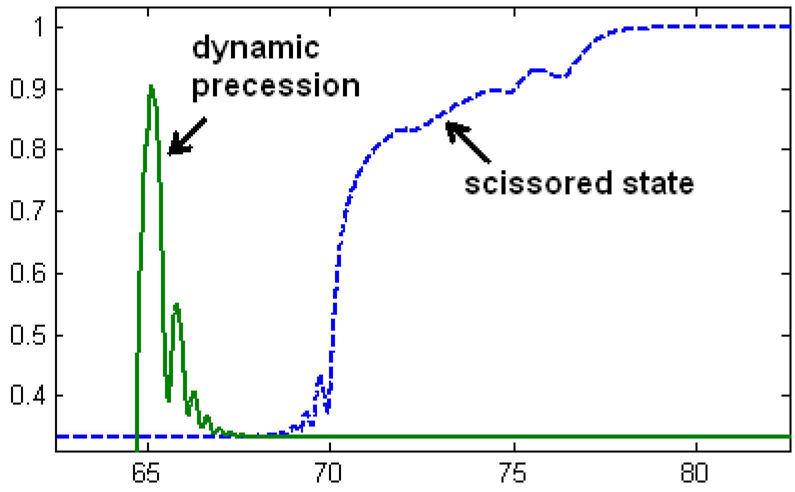

FIG.4. Magnified top right part of the hysteresis loop for J=-40

For stronger AF coupling, this asymmetric scissored state is more dominant. It is not only longer, but appears when the system is approaching saturation and leaves the AF state. In this latter case the appearance of the scissored state is not gradual, but abrupt and therefore accompanied by dynamic precession.

In Fig. 6. one can see the time development of the x component of the moments when the system approaches negative saturation (bottom left of Fig. 5.). The figure shows that the angle β between the 2. moment and the x axis is much higher than the angle α between the 1. and 3. moment and the x axis. From the data about the y and z component of magnetizations we can conclude that the 1. and the 3. moment moves parallel and the 2. moment tries to deviate from them as much as possible to minimize the exchange energy. The exact relation between α and β must be revealed by the analytical calculations.

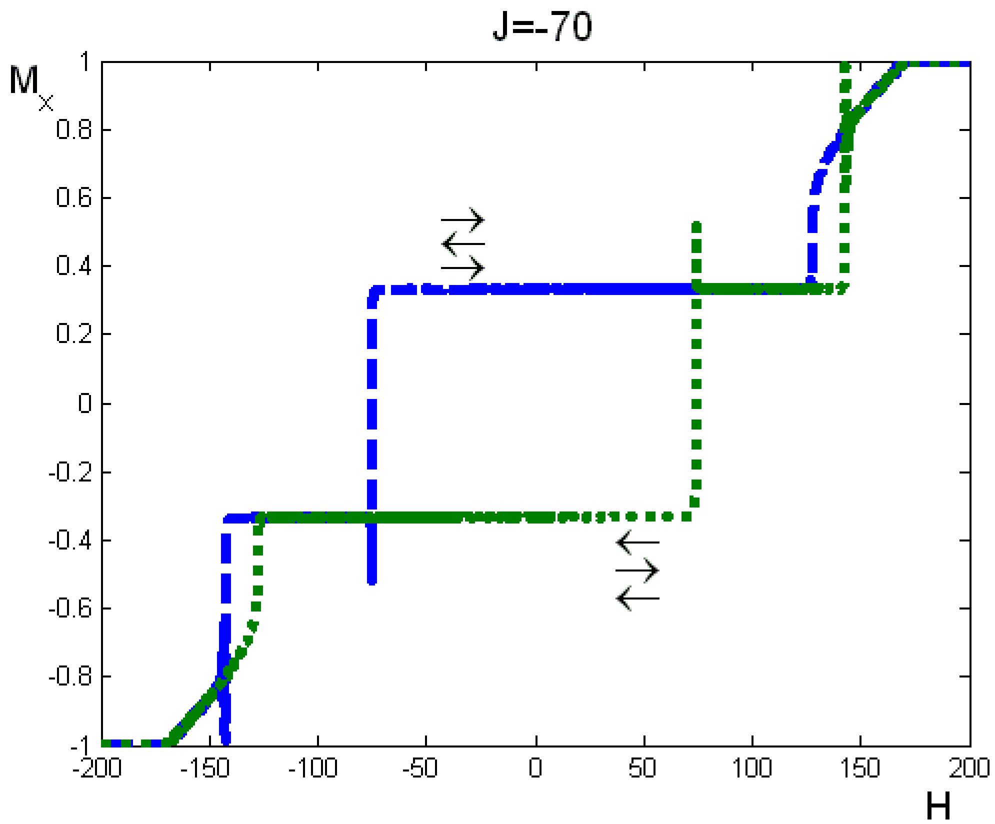

FIG.5. Hysteresis loop for J=-70

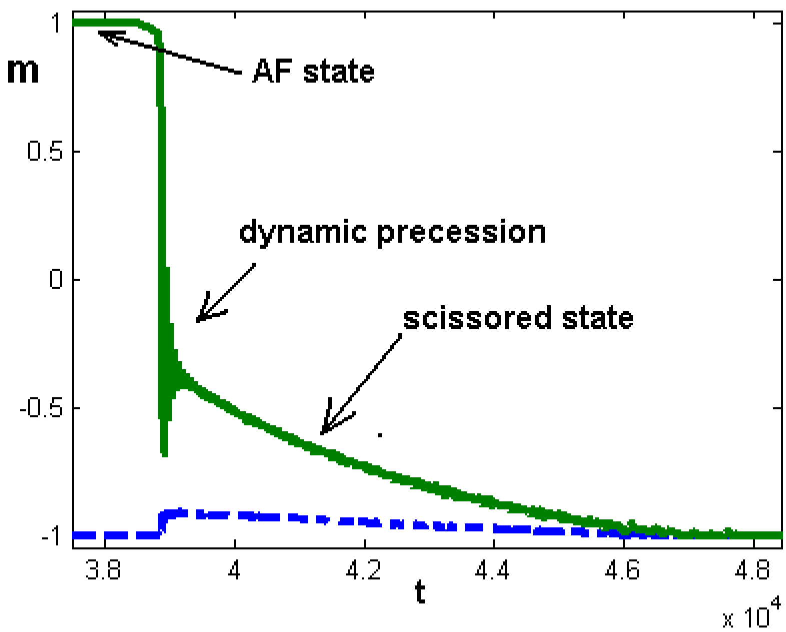

FIG.6. Part of the time development of the system for J=-78. On the horizontal axis t is the time is in numerical timesteps. On the vertical axis, m is the x component of the magnetization of the particles, normalized by one. The blue dashed line indicates the 1. and the 3. particle, while the green continuous line is the 2. particle.

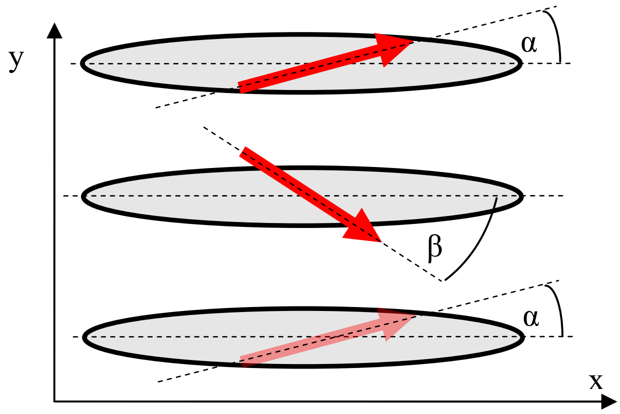

FIG.7. The scissored state

SUMMARY

We have investigated the magnetization reversal in a system that consists of three identical elongated and coupled nanomagnets. Some of the complex dynamical behaviour of the three magnetic element systems has been demonstrated by solving the Landau-Lifshitz-Gilbert equations numerically. The system has different magnetic phases associated with the complicated energy balances of the system that are attributable to the strength of the magnetic field, the coupling and the anisotropy of the particles. The switching between the magnetic states shows non-trivial behaviour. There is a dynamical precession whereby the transition to a different magnetic orientation of the three macrospins occurs with a spike in the average magnetization of the system.

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