Probabilistic aspects of magnetization relaxation in nanomagnets

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A single-domain nanomagnet is a basic example of system where relaxation from high to low energy is probabilistic in nature even when thermal fluctuations are neglected. Several aspects of research in micromagnetics and magnetization dynamics revolve around the central question: under what conditions will an unstable nanomagnet reach a prescribed final magnetization state ? A striking feature revealing that a general answer to this question is far from trivial is the fine interlacing of the basins of attraction of stable magnetization states under zero external field. This interlacing is the consequence of dissipative mechanisms which are a rather weak perturbation of constant-energy precessional dynamics. The result is an extreme sensitivity to initial conditions. As a consequence, a nanomagnet brought to an unstable initial state will relax to a final magnetization orientation which appears to be unpredictable, because control of initial conditions is always imperfect, due to thermal fluctuations or other disturbances.

In the language of dynamical system theory, the picture we are describing is that of a weakly dissipative system where multiple stable states exist and sensitivity to initial conditions introduces probabilistic aspects in an otherwise purely deterministic dynamics. This problem is of very general nature, and is encountered in many other fields of science, from stability of planetary motion in the solar system, to motion of charged particles in electric and magnetic fields, to propagation of electromagnetic waves.

A central role is played in weakly dissipative systems by the notion of averaging and separatrix crossing. The fact is that weak dissipation implies the existence of two distinct time scales: a fast scale on which motion at nearly constant energy takes place; and a slow scale on which energy decreases due to dissipation. The slow relaxation in energy, revealed by averaging over the fast scale, provides the core information about the behavior of the system. However, when the system can relax to multiple low-energy states the energy description becomes incomplete, because one needs additional information about which low-energy state is selected when the system crosses the saddle separatrix between high and low energy. This additional information is expressed in probabilistic terms, by introducing the notion of probability P_i of relaxation from high energies to one of the available stable states s_i.

We demonstrate that in a single-domain nanomagnet the relaxation probabilities P_i can be tuned to whatever desired value between 0 and 1 by applying a small transverse magnetic field. The field neither breaks the mirror symmetry of the energy function with respect to the final stable states nor introduces any important distortion in the energy profile. Nevertheless, the small energy term that is added to the dynamics is enough to alter the effect of the weak dissipative part in a way that drastically modifies the relaxation probabilities. In particular, one can achieve a complete restructuring of the basins of attraction, in which the probability of reaching one of the stable states becomes exactly 0 or 1. Under these conditions, magnetization relaxation is totally insensitive to initial conditions and the final state can be predicted with certainty.