Metastability and Quantum Tunneling

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Except for some technical objections, there seems to be a consensus that quantum coherence has been observed at macroscopic/mesoscopic scales; see [1]-[6], for instance. That is, during the demagnetization with time, t, of fine particles, the magnetic viscosity ν, becomes independent of temperature, T, at low T, which is interpreted as reflecting quantum resonance or tunneling of the (fine-particle) magnetic vectors between two (or more) minima. Our study of some oversimplified models, in which demagnetization consists of escaping from a metastable state and decaying towards a *nonequilibrium* steady state, indicate that such a behavior of $\nu(T)$ could also reflect an intrinsic property of time relaxation in magnets with *microscopic* impurities.

Consider a ferromagnetic 'particle' consisting of Ising spins, $\sigma_i = \pm 1$, where $i = 1, \ldots, N$, the sites of the square lattice with free boundaries. The particle is initially in a metastable state in which $\sigma_i = +1\ \forall i$ under a negative and small external field. Time evolution then proceeds in the computer by competing dynamics: After one spin is selected at random, one attempts flipping it. With probability p, the flip is performed at random to simulate *impure* behavior; with probability $1 - p$, the attempt follows the thermal Metropolis rule. Therefore, the effective rate is $p/2 + (1-p) \min \{1, \exp(-\Delta H/T)\}$, where ΔH is the change of (Ising nearest-neighbor) energy brought about by the attempt, and $T < T_O = 2.2691$, the Onsager critical temperature (in units $J, k_B = 1$). Due to the conflict between the random and thermal processes in this effective rate, detailed balance does not hold so that the particle cannot reach the canonical equilibrium state at any temperature but tends asymptotically as $t \to \infty$ to a nonequilibrium steady state (see [7], for instance). One averages over $\mathcal{N}$ computer runs to simulate an ensemble of independent particles of the same size.

The emergent time evolution exhibits first a rather slow regime (reminding of experiments in which a saturating field is suppressed) such that the magnetization, $m = N^{-1} \sum_i \sigma_i$, is approximately lineal with $\ln t$ defining slope $\nu_1 (T)$, and then an abrupt decay of slope $\nu_2 (T) \gg \nu_1 (T)$ (see [8] for details). Both functions have the same qualitative behavior; in particular, as for experiments, they become constant for $T < T_Q (p)$, which decreases with increasing p; see the figure. Therefore, it may be argued that microscopic impurities occurring rarely, even with probability of order 10^{-6}, within a particle of mesoscopic size ($N = 100 - 4000$ in simulations) that otherwise relaxes by a thermal process, would cause an observable effect which is similar to the one reported in experiments. The mentioned impurities might represent, for example, microscopic magnetic elements of the particle that individually perform quantum tunneling instead of behaving coherently with the rest.

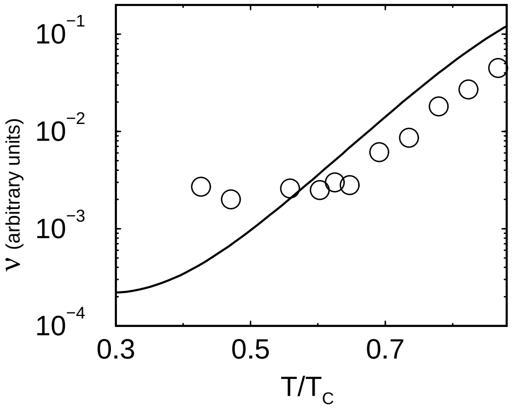

Figure: *emperature dependence of the magnetic viscosity he circles are for* $\nu_1 (T)$ *from simulations here* $p = 10^{-6}$, $L = 32$ *the solid line is* $\nu_\tau (T)$ *for a related meanfield model* [8] $p = 0.1$; $\tau = 4$, *in arbitrary units*

This conclusion is reinforced by investigating analytically some related models. The simplest nontrivial case with exact solution is a chain of L binary spins, $L + 1 \equiv 1$, that, after a field is suppressed, relax with effective rate $p +$

$(1-p)\left[1-\frac{\gamma}{2}\sigma_i(\sigma_{i-1}+\sigma_{i+1})\right]$, where $\gamma=\tanh\left(2T^{-1}\right)$. It follows (for either finite L or $L\to\infty$) that $m\left(t\right)=\exp\left[-2t\left(1-\gamma_{eff}\right)\right]$, $\gamma_{eff}=\left(1-p\right)\gamma$, and one may define an *instant viscosity*, $\nu_{\tau}\left(T\right)\equiv-\left[t\left(\partial m/\partial t\right)\right]_{t=\tau}=2\tau\left(1-\gamma_{eff}\right)m\left(\tau\right)$, which has the same qualitative behavior as $\nu_1\left(T\right)$ and $\nu_2\left(T\right)$ for typical values of τ (figure). Therefore, the mentioned experimental observation seems a rather general, intrinsic feature of systems in which impure behavior induces competing dynamics (that leads asymptotically, in general, to nonequilibrium steady states [7]). As $T\to 0$, $\nu_{\tau}\left(T\right)\to 2p\tau\exp\left(-2p\tau\right)$, namely, constant behavior of the viscosity at low T follows for any $p>0$: one only needs to adapt conveniently the observation scale so that $p\tau$ is finite. That is, T-independence of demagnetization processes, which has some important technological consequences, besides other possible origins, seems to be an intrinsic feature of time relaxation in natural systems.

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