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Brownian motion of massive skyrmions in magnetic thin films

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ABSTRACT

We report on the thermal effects on the motion of current-driven massive magnetic skyrmions. The reduced equation for the motion of skyrmion has the form of a stochastic generalized Thiele's equation. We propose an ansatz for the magnetization texture of a non-rigid single skyrmion that depends linearly with the velocity. By using this ansatz it is found that the skyrmion mass tensor is closely related to intrinsic skyrmion parameters, such as Gilbert damping, skyrmion-charge and dissipative force. We have found an exact expression for the average drift velocity as well as the mean-square velocity of the skyrmion. The longitudinal and transverse mobility of skyrmions for small spin-velocity of electrons is also determined and found to be independent of the skyrmion mass.

1. Introduction

Skyrmions are vortex-like spin structures that are topologically protected and have recently been the focus of intense research in condensed matter [1,2]. Skyrmions were originally conceived in nuclear physics to describe interacting pions [1], however have found versatile application in a variety of different areas in physics [3–5]. A series of works reports their recent observation in chiral magnets [6–11]. There is a great interest in their dynamics due to the potential applications

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in spintronics that arise from the rather low current densities that are necessary to manipulate their location [12]. Among other systems that have been reported hosting skyrmion textures they were observed in bulk magnets MnSi [6,7], $Fe_{1-x}Co_xSi$ [8,9,13], $Mn_{1-x}Fe_xGe$ [14] and FeGe [15] by means of neutron scattering and Lorentz transmission electron microscopy. Regarding their dimensions, by the proper tuning of external magnetic fields, sizes of the order of a few tens of nanometers have been reported. Spin transfer torques can be used to manipulate and even create isolated skyrmions in thin films as shown by numerical simulations [16–18]. In thin films skyrmions have been observed at low temperatures, however energy estimates predict the stability of isolated skyrmions even at room temperatures [19]. Under that regime the motion of skyrmions is affected by fluctuating thermal torques that will render their trajectories into stochastic paths very much like the Brownian dynamics of a particle. Proper understanding of such Brownian motion is a very important aspect of skyrmion dynamics. Numerical simulations [20,21] and experimental results [22], suggest that the skyrmion position can be manipulated by exposure to a thermal gradient and that the skyrmions also display a thermal creep motion in a pinning potential [23]. The thermally activated motion of pinned skyrmions has been studied in Ref. [24] where it has been reported that thermal torques can increase the mobility of skyrmions by several orders of magnitude. In this work we present a study of the random motion of magnetic skyrmions arising from thermal fluctuations. In our analysis we include an assessment of the deformation of the skyrmion that arises from its motion. This deformation induces an inertia-like term into the effective stochastic dynamics of the skyrmion. We present a theory that allows us to establish a relation between the fluctuating trajectory of the skyrmion and its effective mass.

2. Brownian skyrmion dynamics

We begin our analysis from the stochastic Landau–Lifschitz–Gilbert (LLG) equation [25,26] that rules the dynamics of the magnetization direction $\mathbf{\Omega}$. Into this equation we need to include the adiabatic, given by $-\mathbf{v}_s \cdot \nabla\mathbf{\Omega}$, and non-adiabatic, given by $\beta\mathbf{v}_s \cdot \nabla\mathbf{\Omega}$, spin-transfer torques [27,28] where the strength of the non-adiabatic spin-transfer torque is characterized by the parameter β. In those expressions $\mathbf{v}_s = -\left(pa^3/2eM\right)\mathbf{j}$ stands for the spin-velocity of the conduction electrons, p is the spin polarization of the electric current density $\mathbf{j}$, $e(> 0)$ the elementary charge, a the lattice constant, and M the magnetization saturation. With those contributions the stochastic Landau–Lifshitz–Gilbert equation becomes:

$$\left(\frac{\partial}{\partial t} + \mathbf{v}_s \cdot \nabla\right)\mathbf{\Omega} = \mathbf{\Omega} \times (\mathbf{H}_{\text{eff}} + \mathbf{h}) + \alpha\mathbf{\Omega} \times \left(\frac{\partial}{\partial t} + \frac{\beta}{\alpha}\mathbf{v}_s \cdot \nabla\right)\mathbf{\Omega}, \tag{1}$$

where $\mathbf{H}_{\text{eff}} = \frac{1}{\hbar}\frac{\delta E}{\delta\mathbf{\Omega}}$ is the effective field, with E representing the energy of the system, and α the Gilbert damping constant. An important aspect of this equation is the inclusion of the white Gaussian fluctuating magnetic field $\mathbf{h}$, describing the thermal agitation of the magnetization and obeying the fluctuation–dissipation theorem [25,29]. The strength of the noise, $\sigma = 2\alpha k_B Ta^2/\hbar$, is proportional to the thermal energy k_BT, the Gilbert damping parameter α, and the volume of the finite element grid a^2.

Solutions of the Landau–Lifshitz–Gilbert equations exhibit analogies with a very large variety of physical systems such as particle-like or spin waves. For example, it has been shown that spin-waves display the Bose–Einstein condensation transition phenomena in magnetic thin films [30–32]. Additionally, particle-like solutions, representing compact magnetic textures moving as coherent entities with a well defined velocity, have known since long ago. Among other examples we can found the dynamics of domain walls [33,34] and of Bloch points [35,36]. The account of the dynamics of skyrmion textures is best handled by the use of the collective coordinates approach. Under this framework the complex dynamics of the magnetization texture, $\mathbf{\Omega}(\mathbf{r}, t)$ is reduced to the evolution of a small number of degrees of freedom given by the skyrmion position and its velocity. In this way the magnetization field associated to a single-skyrmion moving along the trajectory $\mathbf{x}(t)$ is represented by a magnetization profile $\mathbf{\Omega}(\mathbf{r}, t) = \mathbf{\Omega}(\mathbf{r} - \mathbf{x}(t), \mathbf{v}(t))$. The explicit time-dependence of the magnetization, coming from the dependence on velocity $\mathbf{v}(t)$, includes the effects of deformations of the skyrmion [37–39]. The calculation for the static skyrmion profile, $\mathbf{\Omega}_0(\mathbf{r})$, has been addressed elsewhere [40], by means of a minimization of the magnetic energy. In this energy the contributions from