

Chapter 5

Regulating spin dynamics of dipolar and spinor atoms

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5.1 Introduction

One of the most important problems in spintronics is the ability of fast regulation of spin dynamics. This ability is indispensable for the creation of different devices, such as memory storages, using the interaction of effective system spins with magnetic fields. The functioning of memory devices usually confronts the necessity of overcoming two contradictory requirements. From one side, for keeping the memory for long time, it is necessary to be able to freeze the spin direction, while from the other side, it is required, when necessary, to quickly change this direction.

In this communication, we describe some methods, developed by the authors, allowing for fast regulation of spin motion. These methods can be applied to different systems enjoying magnetic moments. In order to achieve coherent spin dynamics, it is customary to employ nanosize objects, such as magnetic nanomolecules [1–19], magnetic nanoclusters [7, 12, 15, 18–27], magnetic graphene, where magnetism is induced by magnetic defects [28–33], trapped atoms and molecules interacting through dipolar or spinor forces [34–40], magnetic quantum dots [41–44], polarized nanomolecules [4, 45], and magnetic hybrid materials [46].

The method we have suggested is based on the use of the combination of a magnetic material and an electric circuit creating a magnetic feedback field. This method can be applied to various magnetic materials. Of course, different materials are described by different Hamiltonians, which requires to employ some special tricks for being able to effectively regulate their spin motion, however the basic ideas remain the same.

5.2 Magnetic nanomolecules and nanoclusters

The main ideas employed for regulating spin dynamics can be most easily explained by the example of spin dynamics in magnetic nanomolecules and nanoclusters.

Magnetic nanomolecules have the sizes of nanometers. A molecule potential topography can be described by a double-well potential, where the spin possesses two easy directions that can be called "spin up" and "spin down". Below the blocking temperature $T_B \sim 1 - 10$ K, the spin becomes frozen in one of the directions due to the magnetic anisotropy field $E_A \sim 10 - 100$ K. The total spin of the molecule ground state can vary between $1/2$ and $27/2$. Thus the widely studied molecules of Mn_{12} or Fe_8 have the spin $S = 10$.

Magnetic clusters are characterized by the similar properties, although they are much larger than molecules, being of the radius $R_{coh} \sim 10 - 100$ nm and containing about $100 - 10^5$ magnetic particles. Below the blocking temperature $T_B \sim 10 - 100$ K, the cluster spin is frozen in one of the easy directions. Magnetic nanoclusters have to be of nanosizes mentioned above in order that the spins of particles forming the clusters be coherent with each other and the specimen would not separate into several domains. Magnetic particles of the sizes $R > R_{coh}$ become separated into several magnetic domains, so that the total spin becomes close to zero. There exists a very large variety of magnetic clusters composed of pure metals, such as Fe, Ni, and Co, and of various oxides and alloys.

The dilemma, one confronts when creating memory devices, is as follows. From one side, to keep the fixed memory intact for long time, one needs to possess a rather strong magnetic anisotropy, while from the other side, to be able to quickly change the spin direction, in order to erase the memory or to correct the stored content, one has to be able to quickly regulate spin dynamics.

Magnetic nanomolecules and nanoclusters are described by the similar Hamiltonians, such as

$$\hat{H} = -\mu_S \mathbf{B} \cdot \mathbf{S} - DS_z^2 + E(S_x^2 - S_y^2), \quad (5.1)$$

where μ_S is magnetic moment, \mathbf{B} is the total magnetic field acting on the specimen, \mathbf{S} is the spin operator, D and E are anisotropy parameters. The total magnetic field is the superposition

$$\mathbf{B} = (B_0 + \Delta B)\mathbf{e}_z + H\mathbf{e}_x + B_1\mathbf{e}_y \quad (5.2)$$

of a constant magnetic field B_0 , regulated field ΔB , anisotropy field B_1 , and a feedback field H .

The overall setup is organized according to the scheme of Fig. 5.1, where the studied magnetic sample is inserted into a magnetic coil of an electric circuit playing the role of a resonator. The spin is in a metastable state, being frozen due to the low temperature and strong magnetic anisotropy. The moving spin of the sample creates electric current in the circuit that forms the feedback field acting on the sample. The feedback field satisfies the

equation

$$\frac{dH}{dt} + 2\gamma H + \omega^2 \int_0^t H(t') dt' = -4\pi\eta_{res} \frac{dm_x}{dt}, \quad (5.3)$$

in which γ is the circuit attenuation, ω is the circuit natural frequency, $\eta_{res} = V/V_{res}$ is the resonator filling factor, and the electromotive force is created by the moving average spin

$$m_x = \frac{\mu_S}{V} \langle S_x \rangle. \quad (5.4)$$

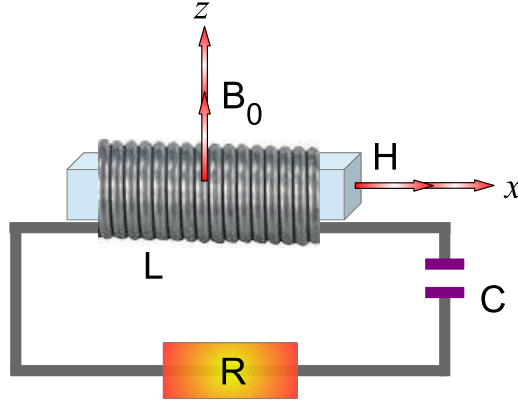


Figure 5.1: Scheme of suggested setup, as is explained in the text.

The equations of motion are written for the spin averages

$$x \equiv \frac{\langle S_x \rangle}{S}, \quad y \equiv \frac{\langle S_y \rangle}{S}, \quad z \equiv \frac{\langle S_z \rangle}{S}. \quad (5.5)$$

Pair spin correlations are decoupled employing the generalized mean-field approximation [6]

$$\langle S_\alpha S_\beta + S_\beta S_\alpha \rangle = \left(2 - \frac{1}{S}\right) \langle S_\alpha \rangle \langle S_\beta \rangle, \quad (5.6)$$

where $\alpha \neq \beta$ and which is exact for $S = 1/2$ and asymptotically exact for $S \gg 1$.

Let us introduce the notations for the Zeeman frequency

$$\omega_0 \equiv -\frac{\mu_S}{\hbar} B_0 \quad (5.7)$$

and the anisotropy frequencies

$$\omega_D \equiv (2S - 1) \frac{D}{\hbar}, \quad \omega_E \equiv (2S - 1) \frac{E}{\hbar}, \quad \omega_1 \equiv -\frac{\mu_S}{\hbar} B_1. \quad (5.8)$$

The dimensionless anisotropy parameter is

$$A \equiv \frac{\omega_D + \omega_E}{\omega_0}. \quad (5.9)$$

The dimensionless regulated field is defined as

$$b \equiv - \frac{\mu_S \Delta B}{\hbar \omega_0} . \quad (5.10)$$

The coupling between the magnetic sample and the resonator is characterized by the coupling rate

$$\gamma_0 \equiv \pi \eta_{res} \frac{\mu_S^2 S}{\hbar V} . \quad (5.11)$$

Also, introduce the notation for the dimensionless feedback field

$$h \equiv - \frac{\mu_S H}{\hbar \gamma_0} . \quad (5.12)$$

Then the equations of spin motion read as

$$\begin{aligned} \frac{dx}{dt} &= -\omega_S y + \omega_1 z , & \frac{dy}{dt} &= \omega_S x - \gamma_0 h z , \\ \frac{dz}{dt} &= 2\omega_E x y - \omega_1 x + \gamma_0 h y , \end{aligned} \quad (5.13)$$

where

$$\omega_S \equiv \omega_0(1 + b - Az) \quad (5.14)$$

plays the role of an effective rotation frequency.

In the dimensionless notation, the feedback-field equation becomes

$$\frac{dh}{dt} + 2\gamma h + \omega^2 \int_0^t h(t') dt' = 4 \frac{dx}{dt} . \quad (5.15)$$

Efficient interaction between the electric circuit and the magnetic sample occurs when there happens a resonance between the effective Zeeman frequency ω_S of the sample spins and the resonator natural frequency ω . However, because of the presence of the anisotropy term, such a resonance cannot occur, since the detuning

$$\frac{\omega_S - \omega}{\omega_0} = \frac{\Delta\omega}{\omega_0} + b - Az \quad (\Delta\omega \equiv \omega_0 - \omega) \quad (5.16)$$

can be very large.

One of the possibilities for overcoming the above problem is to resort to the method of *triggering resonance* [18]. Assume that we need to overturn the spin at the moment of time τ . Then, tuning ω to ω_0 , the regulated part of the magnetic field $b(t)$ is kept zero before the time τ , and is switched on at the time τ , so that

$$b(t) = \begin{cases} 0 , & t < \tau \\ Az_0 , & t \geq \tau \end{cases} . \quad (5.17)$$

At this initial moment of time τ , when the spin polarization is z_0 , the effective detuning becomes small,

$$\frac{\omega_S - \omega}{\omega_0} = b(\tau) - Az_0 = 0 \quad (t = \tau) , \quad (5.18)$$

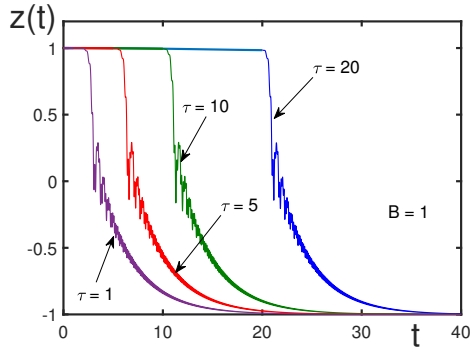


Figure 5.2: Spin polarization of a nanomagnet as a function of time for the parameters $\omega = \omega_0 = 10$, $\omega_E = \omega_1 = 0.01$, $\gamma = 1$, with the fixed triggering resonance condition $B \equiv b(\tau) = Az_0 = 1$ and varying delay time τ

which triggers the fast motion of spin reversal. Although the overall reversal is rather fast, but there appear tails, as is seen in Fig. 5.2.

To preserve the resonance condition for the whole time of spin reversal, the method of *dynamic resonance tuning* is suggested [19]. Then the regulated field $b = b(t)$ is varied so that to compensate the temporal variation of the anisotropy term $Az = Az(t)$. That is, the regulated field is switched on so that

$$b(t) = \begin{cases} 0, & t < \tau \\ Az_{reg}(t), & t \geq \tau \end{cases}, \quad (5.19)$$

which makes the effective detuning close to zero,

$$\frac{\omega_S - \omega}{\omega_0} = A[z_{reg}(t) - z(t)] \ll 1, \quad (5.20)$$

when $\omega = \omega_0$. The regulated polarization z_{reg} is modeled by an explicit expression or given equations. This method provides ideal conditions for keeping the spin frozen before the required time τ and then, at time τ , reversing the spin, as shown in Fig. 5.3.

5.3 Assemblies of nanomolecules or nanoclusters

It is possible to consider assemblies of nanomolecules or nanoclusters, when the system Hamiltonian has the form

$$\hat{H} = -\mu_S \sum_i \mathbf{B} \cdot \mathbf{S}_i + \hat{H}_A + \hat{H}_D, \quad (5.21)$$

where the first term is the Zeeman energy, the second term is the anisotropy energy

$$\hat{H}_A = - \sum_j \{ D(S_j^z)^2 - E [(S_j^x)^2 - (S_j^y)^2] \}, \quad (5.22)$$

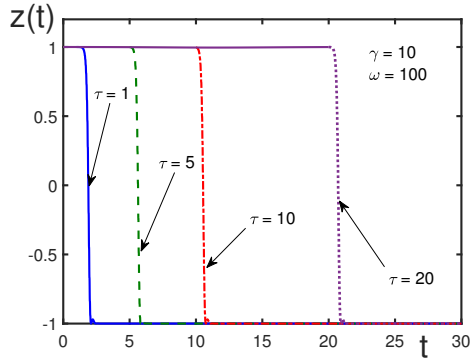


Figure 5.3: Spin polarization $z(t)$ of a nanocluster or nanomolecule as a function of time under dynamic resonance tuning, starting at different delay times: $\tau = 1$ (solid line), $\tau = 5$ (dashed line), $\tau = 10$ (dash-dotted line), and $\tau = 20$ (dotted line). Other parameters are fixed as $A = 1$, $\omega_E = \omega_1 = 0.01$, $\omega = \omega_0 = 100$ and $\gamma = 10$.

and, in addition, it is necessary to take account of the dipolar interactions through the dipolar tensor $D_{ij}^{\alpha\beta}$,

$$\hat{H}_D = \frac{1}{2} \sum_{i \neq j} \sum_{\alpha\beta} D_{ij}^{\alpha\beta} S_i^\alpha S_j^\beta. \quad (5.23)$$

The total magnetic field can be taken as

$$\mathbf{B} = (B_0 + \Delta B)\mathbf{e}_z + H\mathbf{e}_x. \quad (5.24)$$

The anisotropy parameter E usually is much smaller than D , because of which one takes the anisotropy term as

$$\hat{H}_A = - \sum_j D(S_j^z)^2. \quad (5.25)$$

The dynamics of the summary spin is similar to that of the spins of single nanosamples [5, 7–10, 12, 15, 23–25, 27]. The role of the dipolar interactions is two-fold. First, the dipolar spin interactions trigger the initial spin motion by creating spin waves, and second, they result in the transverse spin attenuation leading to the dephasing of spin dynamics. The latter, however, does not strongly influence the coherent spin rotation, if the dephasing time is much longer than the reversal time. For nanomolecules and nanoclusters, the reversal time is of the order

$$t_{rev} \approx \frac{\gamma}{\gamma_0 \omega_0 z_0} \sim 10^{-11} \text{ s}. \quad (5.26)$$

5.4 Other magnetic nanomaterials

Except nanomolecules and nanoclusters, there are several other types of magnetic nanomaterials that can be employed for spintronic devices. Coherent spin motion in these materials can be regulated similarly to the case of nanomolecules and nanoclusters, considered above.

Emergence of defect-induced magnetism in graphene materials has been studied by Yazyev [28] and by Enoki and Ando [31]. Defects in graphene interact with each other through exchange interactions. The spin Hamiltonian consists of two terms, the Zeeman energy and the Heisenberg Hamiltonian,

$$\hat{H} = -\mu_S \sum_i \mathbf{B} \cdot \mathbf{S}_i - \frac{1}{2} \sum_{i \neq j} J_{ij} (S_i^x S_j^x + S_i^y S_j^y + \alpha S_i^z S_j^z) . \quad (5.27)$$

The total magnetic field is the sum as in (5.24), including an external magnetic field and a feedback magnetic field. Peculiarities in the case of exchange interactions have been considered in detail in Ref. [47]. Dynamics of defect spins in graphene are considered in Refs. [32, 33]. Similar dynamics is exhibited by spins of quantum dots and some magnetic hybrid materials.

One more class of magnetic materials is presented by polarized nanomolecules that do not possess spins in their ground state, but nuclear spins inside them can be polarized by means of dynamic nuclear polarization [48–50]. This kind of molecules, for instance, are propanediol, butanol, and ammonia. Being spin polarized, they can keep this polarization for days and months. The Hamiltonian is

$$\hat{H} = -\mu_0 \sum_i \mathbf{B} \cdot \mathbf{S}_i + \hat{H}_D , \quad (5.28)$$

in which the term due to dipolar interactions is

$$\hat{H}_D = \frac{1}{2} \sum_{i \neq j} \frac{\mu_0^2}{r_{ij}^3} [\mathbf{S}_i \cdot \mathbf{S}_j - 3(\mathbf{S} \cdot \mathbf{n}_{ij})(\mathbf{S}_j \cdot \mathbf{n}_{ij})] , \quad (5.29)$$

where

$$\mathbf{n}_{ij} \equiv \frac{\mathbf{r}_{ij}}{r_{ij}} , \quad \mathbf{r}_{ij} \equiv \mathbf{r}_i - \mathbf{r}_j , \quad r_{ij} \equiv |\mathbf{r}_{ij}| .$$

The dipolar Hamiltonian (5.29) can be represented in the form (5.23), with the dipolar tensor

$$D_{ij}^{\alpha\beta} = \frac{\mu_0^2}{r_{ij}^3} \left(\delta_{\alpha\beta} - 3n_{ij}^\alpha n_{ij}^\beta \right) . \quad (5.30)$$

The binary mixture of nuclear and electron spins makes the effective spin-resonator coupling larger, thus diminishing the reversal time [6, 51, 52].

5.5 Trapped spinor atoms

Many atoms and molecules possessing dipolar or angular momenta can be confined in traps forming trapped clouds [34–40]. The derivation of an effective spin Hamiltonian for these objects goes in the following steps [39].

Let us assume that an atom has angular momentum

$$\mathbf{F} = [\mathbf{F}_{mn}] = \sum_\alpha [F_{mn}^\alpha] \mathbf{e}_\alpha , \quad (5.31)$$

where $\alpha = x, y, z$, the quantum magnetic number takes the values $m = -F, -F + 1, -F + 2, \dots, F - 2, F - 1, F$. The field operators of atoms are the columns in the space of the magnetic number,

$$\psi(\mathbf{r}, t) = [\psi_m(\mathbf{r}, t)] .$$

The Hamiltonian of a system composed of such atoms consists of several terms:

$$\hat{H} = \hat{H}_0 + \hat{H}_{LZ} + \hat{H}_{QZ} + \hat{H}_F + \hat{H}_D , \quad (5.32)$$

where

$$\hat{H}_0 = \int \psi^\dagger(\mathbf{r}) \left[-\frac{\nabla^2}{2m} + U(\mathbf{r}) \right] \psi(\mathbf{r}) d\mathbf{r} \quad (5.33)$$

is a single-atom term without a magnetic field, the second part is a linear Zeeman term, the third part is a quadratic Zeeman term, the fourth part represents local atomic interactions, and the last part describes dipolar interactions. For the compactness of the formulas, here and in what follows, we set the Planck constant \hbar to one.

The linear Zeeman term is the standard expression

$$\hat{H}_{LZ} = -\mu_F \int \psi^\dagger(\mathbf{r}) \mathbf{B} \cdot \mathbf{F} \psi(\mathbf{r}) d\mathbf{r} , \quad (5.34)$$

where μ_F is the atomic magnetic moment.

The quadratic Zeeman term consists of the sum

$$\hat{H}_{QZ} = Q_Z \int \psi^\dagger(\mathbf{r}) (\mathbf{B} \cdot \mathbf{F})^2 \psi(\mathbf{r}) d\mathbf{r} + q_Z \int \psi^\dagger(\mathbf{r}) (F_z)^2 \psi(\mathbf{r}) d\mathbf{r} , \quad (5.35)$$

in which the first term in the write-had side describes static-current quadratic Zeeman effect and the second term, alternating-current quadratic Zeeman effect.

The nonresonant static-current quadratic Zeeman effect arises in atoms possessing hyperfine structure, hence a nonzero nuclear spin [53–58]. The static-current quadratic Zeeman-effect parameter reads as

$$Q_Z = \mp \frac{\mu_F^2}{\Delta W (1 + 2I)^2} , \quad (5.36)$$

where ΔW is a hyperfine energy splitting and I is nuclear spin. The sign minus or plus in the static-current Zeeman parameter Q_Z is defined by the relative alignment of the nuclear and the total electron spin projections of the atom: minus for parallel projections, while plus for antiparallel projections.

The quasi-resonant alternating-current quadratic Zeeman effect is due to the alternating-current Stark shift caused either by applying a linearly polarized microwave driving field inducing hyperfine transitions [59–61] or by applying off-resonance linearly polarized light inducing transitions between internal spin states [62–65]. The alternating-current quadratic Zeeman effect parameter is

$$q_Z = -\frac{\Omega_R^2}{4\Delta} , \quad (5.37)$$

where Ω_R is the Rabi frequency of the driving alternating field and Δ is the detuning from an internal, spin or hyperfine, transition.

Local atomic interactions are presented by the Hamiltonian

$$\hat{H}_F = \frac{1}{2} \sum_{klmn} \int \psi_k^\dagger(\mathbf{r}) \psi_l^\dagger(\mathbf{r}) \Phi_{klmn} \psi_m(\mathbf{r}) \psi_n(\mathbf{r}) d\mathbf{r}, \quad (5.38)$$

in which Φ_{klmn} is a matrix element of the interaction potential

$$\Phi_F(\mathbf{r}) = \delta(\mathbf{r}) \sum_f 4\pi \frac{a_f}{m} \hat{P}_f, \quad (5.39)$$

where a_f is the scattering length of a pair of atoms with the angular momentum of the pair f and \hat{P}_f is a projection operator onto a state with an even angular momentum f .

The last term in (5.32) describes dipolar interactions,

$$\hat{H}_D = \frac{\mu_F}{2} \sum_{klmn} \int \psi_k^\dagger(\mathbf{r}) \psi_l^\dagger(\mathbf{r}') D_{klmn}(\mathbf{r} - \mathbf{r}') \psi_m(\mathbf{r}') \psi_n^\dagger(\mathbf{r}) d\mathbf{r} d\mathbf{r}' \quad (5.40)$$

through the regularized screened dipolar tensor

$$D_{klmn}(\mathbf{r}) = \Theta(r - b_F) D_{klmn}^0(\mathbf{r}) \exp(-\varkappa_F r),$$

$$D_{klmn}^0(\mathbf{r}) = \frac{1}{r^3} [(\mathbf{F}_{kn} \cdot \mathbf{F}_{lm}) - 3(\mathbf{F}_{kn} \cdot \mathbf{n})(\mathbf{F}_{lm} \cdot \mathbf{n})], \quad (5.41)$$

in which

$$r = |\mathbf{r}|, \quad \mathbf{n} = \frac{\mathbf{r}}{r}.$$

The potential regularizing and screening take into account the finite sizes of atoms or molecules and the matter around them [40].

5.6 Insulating optical lattices

Trapped atoms can be loaded into deep optical lattices, formed by laser beams, where the atoms become well localized and do not jump between lattice sites [66–69]. Then the lattice is called insulating. For a periodic lattice, the field operators can be expanded over Wannier functions,

$$\psi_m(\mathbf{r}) = \sum_j c_{jm} w(\mathbf{r} - \mathbf{a}_j), \quad (5.42)$$

keeping in mind that at low temperature, the single-band approximation is valid. For an insulating lattice, the Wannier functions can be chosen to be well localized [70], so that the localization conditions be valid:

$$\int w^*(\mathbf{r} - \mathbf{a}_i) f(\mathbf{r}) w(\mathbf{r} - \mathbf{a}_j) d\mathbf{r} \simeq \delta_{ij} f(\mathbf{a}_j),$$

$$\int |w(\mathbf{r} - \mathbf{a}_i)|^2 f(\mathbf{r}) |w(\mathbf{r} - \mathbf{a}_j)|^2 d\mathbf{r} \simeq \delta_{ij} f(\mathbf{a}_j) \int |w(\mathbf{r} - \mathbf{a}_i)|^4 d\mathbf{r},$$

where $f(\mathbf{r})$ is a smooth function of \mathbf{r} .

Let us introduce the local spin operator

$$\mathbf{S}_j = \sum_{mn} c_{jm}^\dagger \mathbf{F}_{mn} c_{jn} \quad (5.43)$$

satisfying the standard spin algebra for any statistics of c_{jm} , whether Bose or Fermi. The local density of atoms is defined as

$$\hat{n}_j = \sum_m c_{jm}^\dagger c_{jm} . \quad (5.44)$$

In this notation, the single-atom term (5.33) reads as

$$\hat{H}_0 = \sum_j E_j \hat{n}_j , \quad (5.45)$$

where

$$E_j \equiv \int w^*(\mathbf{r} - \mathbf{a}_i) \left[-\frac{\nabla^2}{2m} + U(\mathbf{r}) \right] w(\mathbf{r} - \mathbf{a}_j) d\mathbf{r} . \quad (5.46)$$

The term (5.38) of local atomic interactions, for $F = 1$, becomes

$$\hat{H}_F = \sum_j \left[\frac{b_0}{2} \hat{n}_j (\hat{n}_j + 1) + \frac{b_2}{2} (\mathbf{S}_j^2 - 2\hat{n}_j) \right] , \quad (5.47)$$

with the parameters

$$\begin{aligned} b_0 &= c_0 \int |w(\mathbf{r})|^4 d\mathbf{r} , & b_2 &= c_2 \int |w(\mathbf{r})|^4 d\mathbf{r} , \\ c_0 &= \frac{4\pi}{3m} (a_0 + 2a_2) , & c_2 &= \frac{4\pi}{3m} (a_2 - a_0) , \end{aligned} \quad (5.48)$$

in which a_0 and a_2 are the scattering lengths for collisions of atomic pairs.

The linear Zeeman-effect Hamiltonian (5.34) reduces to

$$\hat{H}_{LZ} = -\mu_F \sum_j \mathbf{B}_j \cdot \mathbf{S}_j . \quad (5.49)$$

And the quadratic Zeeman-effect Hamiltonian (5.35) takes the form

$$\hat{H}_{QZ} = \sum_j [Q_Z (\mathbf{B}_j \cdot \mathbf{S}_j)^2 + q_Z (S_j^z)^2] . \quad (5.50)$$

Here the local magnetic field is

$$\mathbf{B}_j \equiv \mathbf{B}(\mathbf{a}_j) = (B_0 + \Delta B) \mathbf{e}_z + H \mathbf{e}_x . \quad (5.51)$$

The dipolar Hamiltonian (5.40) acquires the form

$$\hat{H}_D = \frac{1}{2} \sum_{i \neq j} \sum_{\alpha\beta} D_{ij}^{\alpha\beta} S_i^\alpha S_j^\beta , \quad (5.52)$$

with the dipolar tensor

$$D_{ij}^{\alpha\beta} = \frac{\mu_F^2}{r_{ij}^3} (\delta_{\alpha\beta} - 3n_{ij}^\alpha n_{ij}^\beta) \exp(-\varkappa r_{ij}) . \quad (5.53)$$

5.7 Spin equations of motion

The spin equations of motion are obtained from the Heisenberg equations

$$i \frac{dS_j^\alpha}{dt} = [S_j^\alpha, \hat{H}]. \quad (5.54)$$

It is straightforward to notice that

$$[S_j^\alpha, \hat{H}_0] = 0, \quad [S_j^\alpha, \hat{H}_F] = 0, \quad (5.55)$$

which is valid for any rotationally symmetric Hamiltonian \hat{H}_F with arbitrary F . Therefore the spin motion is governed only by the spin part of the Hamiltonian,

$$i \frac{dS_j^\alpha}{dt} = [S_j^\alpha, \hat{H}_S], \quad (5.56)$$

with the spin Hamiltonian

$$\hat{H}_S = \hat{H}_{LZ} + \hat{H}_{QZ} + \hat{H}_D. \quad (5.57)$$

Notice that the quadratic Zeeman Hamiltonian enters these equations, and its presence is important for governing spin dynamics [39, 40, 71, 72].

The spin equations of motion can be analyzed in several ways. First, it is possible to resort to quasiclassical approximation, when the spin operators S_j^α are replaced by their averages $\langle S_j^\alpha \rangle$ and the resulting equations are solved numerically. This description is applicable at the coherent stage of spin motion, but it is not suitable for quantum stages of motion, especially at the initial stage of movement, where spin waves, triggering the spin motion, are necessary to initiate it.

The other method is based on the scale separation approach [45]. Then we write down the equations for the averages describing the transverse spin

$$u = \frac{1}{SN} \sum_j \langle S_j^- \rangle, \quad (5.58)$$

coherence intensity

$$w = \frac{1}{(SN)^2} \sum_{i \neq j} \langle S_i^+ S_j^- \rangle, \quad (5.59)$$

and longitudinal spin polarization

$$s = \frac{1}{SN} \sum_j \langle S_j^z \rangle, \quad (5.60)$$

where S_j^\pm are the ladder spin operators. The expressions describing local dipolar fluctuations, responsible for the creation of spin waves, are treated as stochastic variables [6, 39].

Keeping in mind the setup, discussed in Sec. 2, the spin equations of motion are complemented by the equation (5.3) for the feedback magnetic field H or for its dimensionless form

$$h = - \frac{\mu_F H}{\gamma_0} \quad (\gamma_0 \equiv \pi \eta_{res} \gamma_2), \quad (5.61)$$

with $\gamma_2 = \rho\mu_F^2 S$ and ρ being spin density.

To realize good resonance, the attenuations are to be small as compared to the Zeeman frequency

$$\omega_0 = -\mu_F B_0 > 0 . \quad (5.62)$$

In that way, there are several small parameters in the system of equations:

$$\frac{\gamma}{\omega_0} \ll 1 , \quad \frac{\gamma_0}{\omega_0} \ll 1 , \quad \frac{\gamma_2}{\omega_0} \ll 1 , \quad \frac{\gamma_3}{\omega_0} \ll 1 , \quad (5.63)$$

where the spin-wave attenuation γ_3 is

$$\gamma_3 \simeq \frac{\gamma_2^2}{\omega_0} . \quad (5.64)$$

Spin fluctuations are proportional to γ_2 , hence are also small.

In accordance to the small parameters (5.63), the variables u and h are classified as fast, while w and s , as slow. Following the scale separation approach, that is a variant of the Krylov-Bogolubov averaging technique [73], we solve the equations for fast variables u and h , with slow variables fixed. Then we substitute the found fast variables u and h into the equations for the slow variables w and s and average the right-hand sides of these equations for the slow variables over time and random fluctuations, with fixed slow variables w and s . As a result of this procedure, we obtain the guiding-center equations

$$\begin{aligned} \frac{dw}{dt} &= -2w + 2\alpha ws + 2 \frac{\gamma_3}{\gamma_2} s^2 + 2q\alpha\beta w^2 s + 2 \frac{\omega_0}{\gamma_2} q\alpha ws^2 , \\ \frac{ds}{dt} &= -\alpha w - \frac{\gamma_3}{\gamma_2} s - q\alpha\beta w^2 - \frac{\omega_0}{\gamma_2} q\alpha ws , \end{aligned} \quad (5.65)$$

where time is measured in units of $1/\gamma_2$. Here α and β are coupling functions

$$\begin{aligned} \alpha &= \frac{g\gamma^2}{\gamma^2 + \Delta_S^2} (1 + b + As) \{1 - [\cos(\Delta_S t) - \delta_S \sin(\Delta_S t)] e^{-\gamma t}\} , \\ \beta &= - \frac{g\gamma^2}{\gamma^2 + \Delta_S^2} (1 + b + As) \{\delta_S - [\sin(\Delta_S t) + \delta_S \cos(\Delta_S t)] e^{-\gamma t}\} , \end{aligned} \quad (5.66)$$

with the coupling parameter

$$g = \frac{\gamma_0 \omega_0}{\gamma \gamma_2} \quad (5.67)$$

and the notation

$$\Delta_S = \omega - \omega_0 |1 + As| , \quad \delta_S = \frac{\Delta_S}{\gamma} \operatorname{sgn} \omega_S . \quad (5.68)$$

The quadratic Zeeman-effect parameter

$$A = \frac{\omega_0}{\gamma_2} q + \frac{\gamma_2}{\omega_0} p \quad (5.69)$$

is composed of the static-current quadratic Zeeman-effect parameter

$$q = S(2S - 1)\rho Q_Z \quad (5.70)$$

and of the alternating-current quadratic Zeeman-effect parameter

$$p = (2S - 1) \frac{q_Z}{\gamma_2} . \quad (5.71)$$

The effective spin-rotation Zeeman frequency is

$$\omega_S = \omega_0(1 + b + As) , \quad (5.72)$$

where the regulated field $b = b(t)$ and the alternating-current quadratic Zeeman-effect parameter $p = p(t)$ can be varied with time. It is therefore possible to regulate the detuning

$$\frac{\omega_S - \omega_0}{\omega_0} = b(t) - A(t)s(t) \quad (5.73)$$

so that either to make it large or negligibly small, respectively, either to freeze the spin or, by inducing the resonance, to organize a fast spin reversal, as is described in Sec. 2. The required resonance condition is

$$b(t) - A(t)s(t) = 0 . \quad (5.74)$$

To estimate the typical order of the parameters, let us take the values for the atoms of ${}^7\text{Li}$, ${}^{21}\text{Na}$, ${}^{41}\text{K}$, and ${}^{87}\text{Rb}$. The spin density is $\rho \sim 10^{15} \text{ cm}^{-3}$, the attenuation rates are $\gamma_2 \sim 10^2 \text{ s}^{-1}$, $\gamma \sim 10\gamma_2 \sim 10^3 \text{ s}^{-1}$, for a magnetic field $B_0 \sim 10^4 \text{ G}$, we have $\omega_0 \sim 10^{11} \text{ s}^{-1}$, $g \sim \omega_0/\gamma \sim 10^8$.

The static-current parameter $Q_Z \sim 10^{-24} \text{ cm}^3$, and $q \sim \rho Q_Z \sim 10^{-9}$. Also, $\omega_0/\gamma_2 \sim 10^9$, hence the contribution of the static-current effect into A is $q\omega_0/\gamma_2 \sim 1$.

In the case of the alternating current effect, $q_Z \sim 10^5 \text{ s}^{-1}$, then $p \sim q_Z/\gamma_2 \sim 10^3$. Hence the contribution of the alternating-current effect into A is $p\gamma_2/\omega_0 \sim q_Z\omega_0 \sim 10^{-6}$. Thus, the parameter A is mainly due to the static-current quadratic Zeeman effect.

5.8 Conclusion

The methods of regulating spin dynamics in different magnetic materials are studied. These materials include magnetic nanomolecules, magnetic nanoclusters, magnetic graphene, polarized nanomolecules, quantum dots, spinor atoms, and hybrid magnetic structures. The basic setup supposes the use of an electric circuit forming a feedback field acting on the magnetic sample and efficiently accelerating spin reversal. The ultrafast spin reversal can be realized in around 10^{-11} s . The idea of employing a feedback field, in combination with the suggested method of triggering resonance, method of dynamic resonance tuning, and the use of the quadratic Zeeman effect can be applied in spintronics, e.g. for creating memory devices. Since there are many similarities between materials with magnetic moments and those possessing electric moments, the developed ideas and methods can be used for achieving fast reversal of electric dipoles. For instance, this can be employed for fast reversal of polarization in ferroelectrics coupled with electric cavity resonators [74, 75].

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