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Edited by **J. M. Marshall, N. Kirov** *and* **A. Vavrek**

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Editors:

J. M. Marshall
Electronic Materials Centre
University of Wales, Swansea, UK

N. Kirov *and* **A. Vavrek**
Institute of Solid State Physics
Sofia, Bulgaria

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TRANSPORT PROCESSES IN MAGNETIC FILMS WITH ROUGH BOUNDARIES

N.B.Ivanov[#], A.E.Meyerovich and S.Stepaniants
Department of Physics, University of Rhode Island, Kingston, RI 02881-0817, USA
[#] Institute of Solid State Physics, 72 Tzarigradsko Chausse, Sofia 1784, Bulgaria

ABSTRACT

We describe magnetic processes in ferromagnetic and antiferromagnetic films with rough boundaries. The analysis is based on recently developed approach to transport phenomena at rough boundaries[1,2]. We reduce transport equation for magnons in a film with rough walls to an equivalent problem with smooth walls, but with some bulk imperfections. This allows us to express the magnon diffusion coefficient via the correlation function of surface inhomogeneities. This correction to the magnon spectrum determines shifts of pole for magnetic susceptibility and resonance line, correlation function, corrections to neutron or Raman scattering, *etc*. The results can be re-formulated in the form of the effective macroscopic boundary condition on rough walls.

1. Introduction

The effects of surface inhomogeneities are important for all properties of thin films. Recently we developed[1,2] a simple general description for transport processes near rough boundaries. Below we apply this method to magnetic phenomena in thin ferro- and antiferromagnetic films.

We will calculate the corrections to the magnon spectrum caused by scattering from rough walls, and derive the effective macroscopic boundary condition which is equivalent to these corrections. The calculation of the magnon spectrum is performed using a canonical coordinate transformation which flattens the walls, but perturbs the *bulk* Hamiltonian. This perturbation gives rise to an effective collision integral and is easily incorporated into the standard transport theory. As a result, the parameters of the magnon spectrum and the effective macroscopic boundary condition for magnetization will be expressed via the correlation function of surface inhomogeneities.

Let us briefly outline the method[1,2]. We consider a film of the average thickness L with the boundaries $x = L/2 - \xi_1(y,z)$ and $x = -L/2 + \xi_2(y,z)$. The inhomogeneities are small, $\xi_1, \xi_2 << L$, and random, $<\xi_{1,2}> = 0$, with the correlation function $\zeta_{ik}(|s_1 - s_2|) = <\xi_i(s_1)\xi_k(s_2)>$. The final results will be expressed via the Fourier image $\zeta(q)$ of the function $\zeta = \zeta_{11} + \zeta_{22} + 2\zeta_{12}$. The walls become smooth, $x = \pm L/2$, after the coordinate transformation[1,2]

$$X = \frac{x - \xi_1(y,z)/2 + \xi_2(y,z)/2}{1 - \xi_1(y,z)/2L - \xi_2(y,z)/2L}, \quad Y = y, \quad Z = z$$

This transformation, together with the conjugate momentum transformation , $p \to P$, cause the change in the form of the bulk Hamiltonian, $H_0(p) \to H_0(P) + V(P,X,\zeta)$. The effective perturbation $V(P,X,\zeta)$ can be treated within a standard perturbative transport equation as any other bulk perturbation (for simplicity, we ignore all bulk dissipative processes). The emerging transport problem is somewhat similar to usual impurity scattering and can easily be solved.

2. Ferromagnetic films

The main difference between transport of magnons in ferromagnetic films from a general case of transport of particles with quadratic dispersion law in films with rough boundaries[1,2] is associated with strong demagnetizing factors when the external field is perpendicular to the film. In this geometry, the magnon spectrum $\omega_0(k)$ is more complicated than a simple quadratic law in bulk ferromagnets.

As a result of the above coordinate transformation, the unperturbed Hamiltonian (spectrum) of magnons in the film,

$$\omega_0(k) = [\Omega_k(\Omega_k + q^2(\Omega_e - \Omega_i)/k^2)]^{1/2}, \quad \Omega_e = \gamma H_e, \quad \Omega_i = \gamma H_i,$$
$$\Omega_k = \Omega_i + \Omega_0 Jk^2, \quad \Omega_0 = \gamma M_0, \quad H_i = H_e - 4\pi M_0,$$

acquires the following "perturbation":

$$\omega(k) = \omega_0(k) + V(k,R), \quad V(k,R) = 2k_x^2\omega_x\xi/L + 2(X/L)k_x\omega_q q\cdot\partial\xi/\partial R,$$
$$\omega_x = \partial\omega_0/\partial(k_x^2), \quad \omega_q = \partial\omega_0/\partial(q^2)$$

where H_e (H_i) is the external (internal) magnetic field, M_0 is the equilibrium ferromagnetic moment in the film, q is the projection of the wave vector k on the plane of the film $\{Y,Z\}$, and the exchange constant J can be expressed via the bulk ferromagnetic exchange integral or the Curie temperature.

This random perturbation leads, after straightforward calculations analogous to[1,2], to the following value of the magnon diffusion coefficient in the plane of the field:

$$D_{yy} = D_{zz} = -\pi\hbar^3 L^2 \int \frac{\partial n_0}{\partial\omega}\frac{\partial\omega_0/\partial k}{\zeta_0-\zeta_1} d\omega \frac{d\cos\theta}{\cos^2\theta\, \alpha\omega_q^2 + 4\omega_x^2\tan^4\theta} \Big/ \int \frac{\partial n_0}{\partial\omega}\frac{\partial\omega_0}{\partial k} d\omega$$

Here

$$\alpha = (\eta_0-\eta_1)/(\zeta_0-\zeta_1), \quad \eta(P,\theta,\phi) = \zeta(P\cos\theta,\phi)[1-\cos\phi]^2,$$

ζ_i and η_i are the Fourier harmonics of the functions ζ and η over the angle ϕ. In the case of Gaussian correlation of the surface inhomogeneities of the average height λ and the correlation radius R, $\alpha = 3/2$, $\zeta_1 = 0$, $\zeta_0 = \zeta(q=P\cos\theta) = 2\pi\lambda^2R^2\exp(-q^2R^2/2\hbar^2)$ [note, that the limit of small correlation radius corresponds to the δ-correlated inhomogeneities with $\zeta_0 = 2\pi\lambda^2R^2$].

As in all other situations considered in [1,2], the appearance of the above wall-induced magnon diffusion coefficient is equivalent to the formation of the effective mean free path in the directions along the walls

$$\Lambda \sim \frac{L^2\hbar^3}{\lambda^2R^2p_M^3} f_M(p_M R/\hbar),$$

where p_M is the characteristic magnon momentum, and $f_M(x)$ is some dimensionless monotonic function of the ratio of the correlation radius of surface inhomogeneities R, to the magnon wavelength.

It is convenient to represent the formation of these wall-induced large relaxation time and magnon diffusion coefficient D in the form of effective attenuation correction to the magnon spectrum:

$$\omega^2(k) = \omega_0(k)[1 - \frac{i\Omega_0^2J^2}{D}\frac{q^2}{\omega_0(k)}]$$

On the other hand, the effective spectrum determines the susceptibility,

$$\chi_{\alpha\beta}(\omega,k) = \frac{\Omega_0^2\kappa_{\alpha\beta}}{\omega^2(k)-\omega^2}, \quad \kappa_{zz} = \kappa_{yy} = \frac{\Omega_k}{\Omega_0}, \quad \kappa_{yz} = -\kappa_{zy} = \frac{i\omega}{\Omega_0},$$

the magnetic structure factor,

$$S_{\alpha\beta}(\omega,k) = i\hbar\frac{\chi^*_{\beta\alpha}(\omega,k) - \chi_{\alpha\beta}(\omega,k)}{1-\exp(-\hbar\omega/T)} = \frac{2\hbar\Omega_0^2\kappa_{\alpha\beta}}{1-\exp(-\hbar\omega/T)}\frac{2\omega\Gamma_k}{(\omega_0^2(k)-\omega^2)^2 + (2\omega\Gamma_k)^2}, \quad \Gamma_k = \frac{\Omega_0^2J^2}{D},$$

and, in essence, all magnetic characteristics of films.

Another way to represent the above results is to incorporate magnon diffusion into the effective macroscopic boundary condition on rough walls,

$$M + \mathcal{L}n_i\nabla_i M = 0$$

where n is the unit vector perpendicular to the wall. Assuming that the wall-induced mean free path is large and $k_x\mathcal{L} >> 1$, the effective length in this boundary condition is

$$\mathcal{L} = \frac{4D}{\Omega_0 JLq^2} \gg \frac{1}{k_x}$$

In the opposite limit $k_x\mathcal{L} << 1$ the expression for $\mathcal{L}$ is somewhat different:

$$\mathfrak{L} = \frac{\Omega_0 J L q^2}{4 k_x^2 D} \ll \frac{1}{k_x}$$

3. Antiferromagnetic films

The calculations for antiferromagnetic films are similar. Here we are dealing with magnons with the linear bulk spectrum,

$$\omega_0(\boldsymbol{k}) = uk,$$

and the diffusion coefficient[1,2]

$$D_{yy} = D_{zz} = -\pi\hbar^3 u^2 L^2 \int \frac{\partial n_0}{\partial\omega} \frac{\omega^2 - u^2 k_x^2}{\zeta_0 - \zeta_1} \frac{d\omega}{\cos^2\theta} \frac{d\cos\theta}{\alpha + 4\tan^4\theta} \Big/ \int \frac{\partial n_0}{\partial\omega} \frac{\omega^2 d\omega}{u^3}$$

The magnon diffusion can be effectively incorporated into the spectrum as

$$\omega(\boldsymbol{k}) = \omega_0(\boldsymbol{k}) - i\Omega_0^2 J^2 q^2 / 4D$$

where, as above, $\Omega_0 = \gamma M_0$, J is the exchange constant, M_0 is the sublattice magnetization, and the velocity of magnons $u = \Omega_0 J$. As a result, the effective susceptibility assumes the form

$$\chi_{yy} = \chi_{zz} - \chi_\perp \frac{\omega^2(\boldsymbol{k})}{\omega^2(\boldsymbol{k}) - \omega^2},$$

while the structure factor is

$$S_{yy,zz}(\omega,\boldsymbol{k}) = \frac{2\hbar\chi_\perp \omega_0^2(\boldsymbol{k})}{1 - \exp(-\hbar\omega/T)} \frac{2\omega\Gamma_k}{(\omega_0^2(\boldsymbol{k}) - \omega^2)^2 + (2\omega\Gamma_k)^2}, \qquad \Gamma_k = \frac{\Omega_0^2 J^2}{4D},$$

As we can see, in both ferro- and antiferromagnetic films the surface-induced diffusion plays the role of diffusion-type attenuation of spin waves along the films. In essence, this is similar to usual bulk results for scattering of magnons by impurities. The only difference is that here, instead of bulk spin diffusion, we have the surface-induced diffusion.

4. References

[1] A.E.Meyerovich and S.Stepaniants, Phys.Rev.Lett., 73, 316,1994; Phys.Rev.B, submitted

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