Contribution to the study of elementary magnetic excitations in multilayer Fe/Pt systems

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Abstract

In this work, we study the elementary excitations and the magnetic properties of the [Fe / Pt] superlattice. The study is obtained within the framework of the Heisenberg model for a ferromagnetic system composed of N atomic planes. We have established a corresponding Heisenberg Hamiltonian taking into account the effect of exchange alone, anisotropy and dipole interactions. The Green function technique was used to diagonalize this Hamiltonian. The excitation spectrum $E_N(k)$ and the spin magnetization $M\ (T)$ are calculated analytically when the exchange is taken into account alone. The adjustment of the theoretical results with the experimental ones is more than satisfactory. This adjustment allowed us to obtain numerical estimates for the volume exchange interaction $(J_\perp)$and the surface exchange interaction $(J_\parallel)$ at various thicknesses of the magnetic layer of Iron (t_{Fe}).

The Calculation Method

To establish an expression of the spin Hamiltonian for studying the properties of the super lattice [Fe/Pt], we consider that this system is made up of a fer layer of N magnetically coupled atomic plans deposited on a platinum layer (Pt). The axis of easy magnetization (OZ) is parallel to the magnetic layer plan (OXZ). The spin Hamiltonian of such a system is then as follows :

$$\mathcal{H} = \mathcal{H}_{ex} + \mathcal{H}_{dip} + \mathcal{H}_{anis} + \mathcal{H}_{ch}$$

$$= -\sum_{\langle ij\rangle} J_{ij}^{\parallel}\left(\left(S_i^x S_j^x + S_i^y S_j^y\right) + \Delta_{ij} S_i^z S_j^z\right) - \sum_{\langle ii'\rangle} J_{ii'}^{\perp}\vec{S_i}\vec{S_j} + \frac{1}{2}\sum_{\langle ij\rangle}\frac{(g\mu_B)^2}{r_{ij}^3}\left(\vec{S_i}\vec{S_j} - 3\frac{(\vec{S_i}.\vec{r_{ij}})(\vec{S_j}.\vec{r_{ij}})}{r_{ij}^2}\right)$$

$$-\alpha\sum_i (S_i^z)^2 - g\mu_B H\sum_i S_i^z \qquad (1)$$

$J_{ij}^{\parallel}$ are the exchange integrals between the first neighbors in the same plan, while $J_{ij}^{\perp}$ correspond to the exchange between two successive plan first neighbors. The surface and the magneto-crystalline anisotropies are represented respectively by α and Δ . Let the constants $\boldsymbol{D} = \frac{(g\mu_B)^2}{r_{ij}^3}$ and $h = g\mu BH$ representing the dipolar interaction and the magnetic field applied along OZ, respectively. Using the Fourier and Holstein-Primakoff transformations [2], the Hamiltonian (1) becomes :

$$\mathcal{H} = \sum_{l,m}^{N}\sum_{k_\parallel}\left\{A_{lm}(k_\parallel)a_{k_\parallel,l}^{+}a_{k_\parallel,m} + \frac{1}{2}B_{lm}(k_\parallel)(a_{k_\parallel,l}^{+}a_{-k_\parallel,m}^{+} + a_{k_\parallel,l}a_{-k_\parallel,m})\right\} \qquad (2)$$

k = (kx, kz) and A_{lm} and B_{lm} are obtained for the plans *l* and *m* (1 ≤ *l* ≤ *N* and 1 ≤ *m* ≤ *N)* by:

$$A_{l,m}(k_\parallel) = S\left\{\sum_{\delta_\parallel}\left[2J_{\delta_\parallel}^{\parallel}\left(1 - \Delta\cos(k_\parallel\delta_\parallel)\right) - \frac{1}{4}D_{\delta_\parallel}\left(\cos(k_\parallel\delta_\parallel) + 2\right)\right]\right.$$
$$\left. + \sum_{\delta_\perp}\left(2J_{\delta_\perp}^{\perp} + \frac{D_{\delta_\perp}}{2}\left(\frac{3}{2}\left(\frac{r_{\delta_\perp}^z}{r_{\delta_\perp}}\right)^2 - 1\right)\right)\left(2 - \delta_{l,1} - \delta_{l,N}\right) + h + 2\alpha\left(\delta_{l,1} + \delta_{l,N}\right)\right\}\delta_{l,m}$$
$$-S\sum_{\delta_\perp}\left(2J_{\delta_\perp}^{\perp} - \frac{D_{\delta_\perp}}{2}\left(\frac{3}{2}\left(\frac{r_{\delta_\parallel}^x}{r_{\delta_\parallel}}\right)^2 - \frac{1}{2}\right)\right)\cos(k_\parallel\delta_\perp)\left(\delta_{l,m-1} + \delta_{l,m+1}\right)$$

$$B_{l,m}(k_\parallel) = S\left(-\frac{3}{4}\sum_{\delta_\parallel}D_{\delta_\parallel}\left(\frac{2r_{\delta_\parallel}^{x^2}}{r_{\delta_\parallel}^2} - 1\right)\cos(k_\parallel\delta_\parallel)\right)\delta_{l,m}$$
$$-\frac{3}{2}S\sum_{\delta_\perp}D_{\delta_\perp}\left(2\left(\frac{r_{\delta_\perp}^x}{r_{\delta_\perp}}\right)^2 + \left(\frac{r_{\delta_\perp}^z}{r_{\delta_\perp}}\right)^2 - 1\right)\cos(k_\parallel\delta_\perp)\left(\delta_{l,m-1} + \delta_{l,m+1}\right)$$

With:

$r_{\delta_\parallel} = (r_{\delta_\parallel}^x, r_{\delta_\parallel}^y, r_{\delta_\parallel}^z)$ are distances between first neighbors in the same plan .

$r_{\delta_\perp} = (r_{\delta_\perp}^x, r_{\delta_\perp}^y, r_{\delta_\perp}^z)$ are distances between first neighbors belonging to two different plans.

Excitation Spectrum

1. The effect of the exchange alone

For$(\alpha = D = h = 0)$ the Hamiltonian (2) becomes:

$$\mathcal{H} = \sum_{k_\parallel,l,m} A_{l,m}^{ex}(k_\parallel)\,a_{k_\parallel,l}^{+}a_{k_\parallel,m}$$

Eigen value matrix:

$$A - E = \begin{pmatrix} A - EI & -W' & 0 & \cdots & 0 \\ -W' & A + W - EI & -W' & \ddots & \vdots \\ 0 & \ddots & \ddots & \ddots & 0 \\ \vdots & \ddots & -W' & A + W - EI & -W' \\ 0 & \cdots & 0 & -W' & A - EI \end{pmatrix} \qquad (3)$$

With,

$$A(k_\parallel) = 2SJ^{\parallel}\left[2\Delta - (\cos(k_x a) + \cos(k_y a))\right] + 4SJ^{\perp}$$

$$W'(k_\parallel) = 4SJ^{\perp}\left(\cos\left(\tfrac{k_x a}{2}\right)\cos\left(\tfrac{k_y a}{2}\right)\right) \quad ; \quad W(k_\parallel) = 4SJ^{\perp}$$

The excitation spectra $E_i^N(k)$ for a plan *l* is obtained in the same way that for analogous magnetic super lattices by solving the secular equation: $det[A - E] = 0$

$$E_i^N(k) = A(k) + \mathcal{E}_i^N(k)$$

$\mathcal{E}_i^N$ are a series of values specifying the solutions of (3).

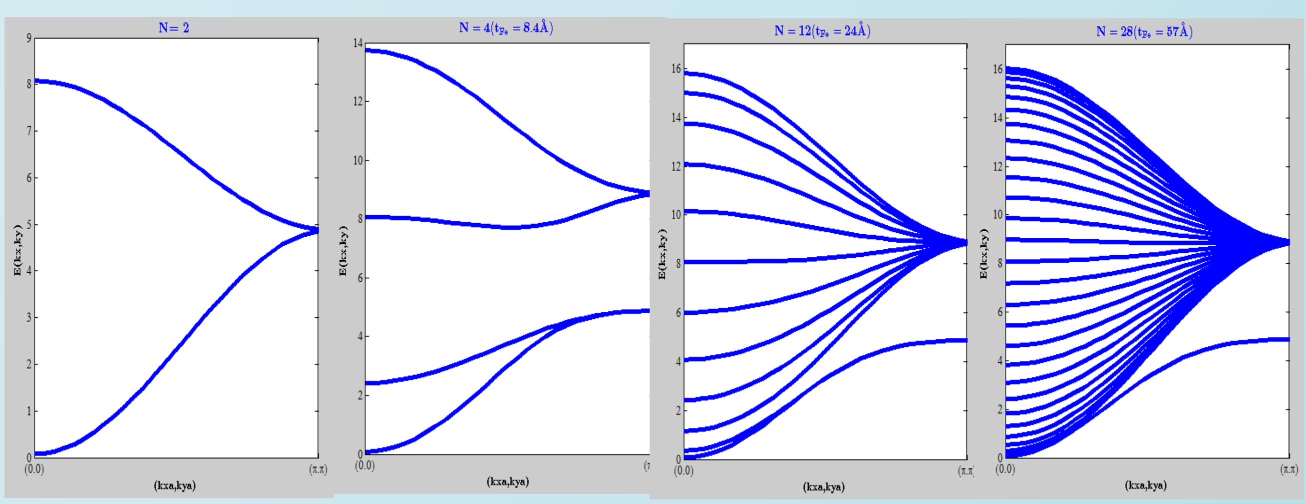

Fig 1-Excitation spectrum $E^N(k)$for different values of the magnetic layer thickness t_{Fe} i.e. number of the N plane with (Δ = 1.2, *S* = 1, $J^{\parallel}$ = 0.1, $J^{\perp}$ = 1,α = 0)

2. The effect of surface anisotropy $\alpha \neq 0$

The Hamiltonian (2) becomes:

$$\mathcal{H} = \sum_{l,m}^{N}\sum_{k_\parallel} A_{lm}^{ex}(k_\parallel)a_{k_\parallel,l}^{+}a_{k_\parallel,m} + 2S\alpha(\delta_{l,1} + \delta_{l,N})a_{k_\parallel,l}^{+}a_{k_\parallel,m}$$

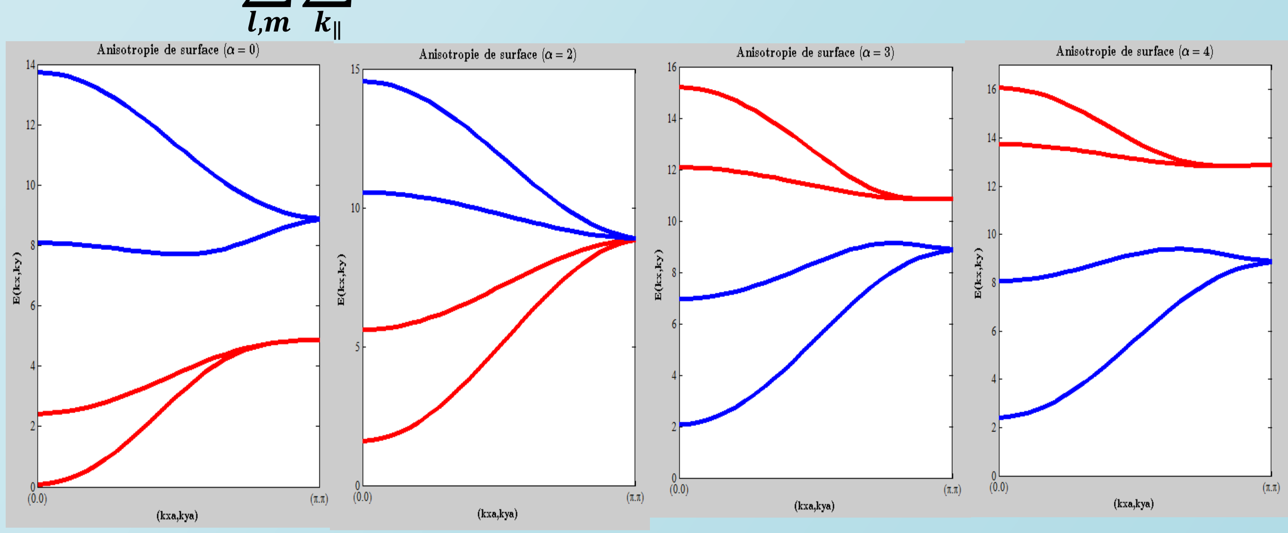

Fig 2 - The effect of different values of surface anisotropy (α = 0; α = 2; α = 3; α = 4) on the excitation spectrum for a thickness t_{Fe} = 8.4A° with (Δ = 1.2, *S* = 1, $J^{\parallel}$ = 0.1, $J^{\perp}$ = 1)

Magnetization Per Spin

The magnetization per spin is expressed in Brillouin zone (BZ) as [3] :

$$M^z(T) = 1 - \frac{1}{S}\frac{1}{N}\frac{s}{(2\pi)^2}\sum_{l=1}^{N}\int\frac{1}{exp\left(\frac{E_l^N(k)}{k_B T}\right) - 1}dk_x dk_y$$

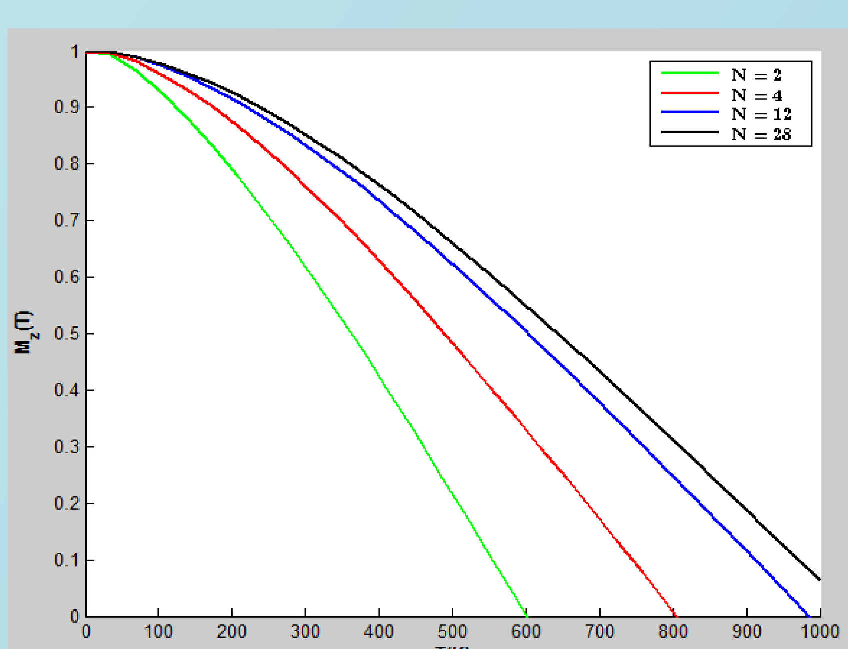

Fig 3- Thermal variation in magnetization of different layer thicknesses magnetic t_{Fe} .

Results Comparison

Comparison between magnetization calculated and measurement results [1],

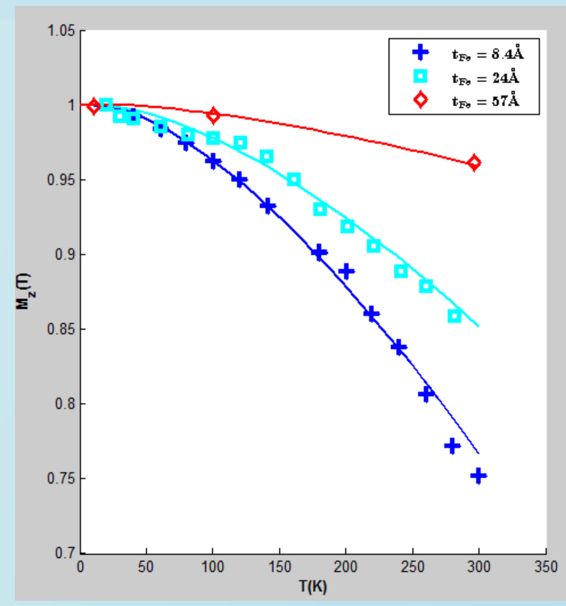

Fig 4- Comparison of the spin magnetization calculation results (continuous curve) with the experimental results (the different symbols).

A comparison of our calculated magnetization $M_{cal}^Z(T)$ with the measured results was made and a good adjustment of these results was obtained. This comparison allowed us to deduce the values of the different magnitudes characteristic of the system under study (F e/Pt) ($J^{\parallel}(k)$, $J^{\perp}(k)$, $T_C(k)$, Δ, $\alpha(k)$).

TABLE 1 - Values of the various characteristic parameters of the F e/Pt system .

t_{Fe}	$J^{\parallel}(k)$	$J^{\perp}(k)$	$T_C(k)$	Δ	α(k)
8,4Å	74	100	750	1,2	6
12Å	80	115	950	1,2	3
57Å	100	340	1400	1,2	1

TABLE 2 - Variation of the different parameters according to different thicknesses of the magnetic layer t_{Fe}

t_{Fe}(Å)	$E_{gs}(k)$	$E_{gb}(k)$	$W_s(k)$	$W_b(k)$	$\tau_s(10^{-6})$	$\tau_b(10^{-6})$
8,4	59,2	859,2	234,3	565,7	6,12	3,87
24	64	137,3	31,3	1685,4	3,38	0,83
57	80	148,2	17,1	5354,7	4,23	1,3

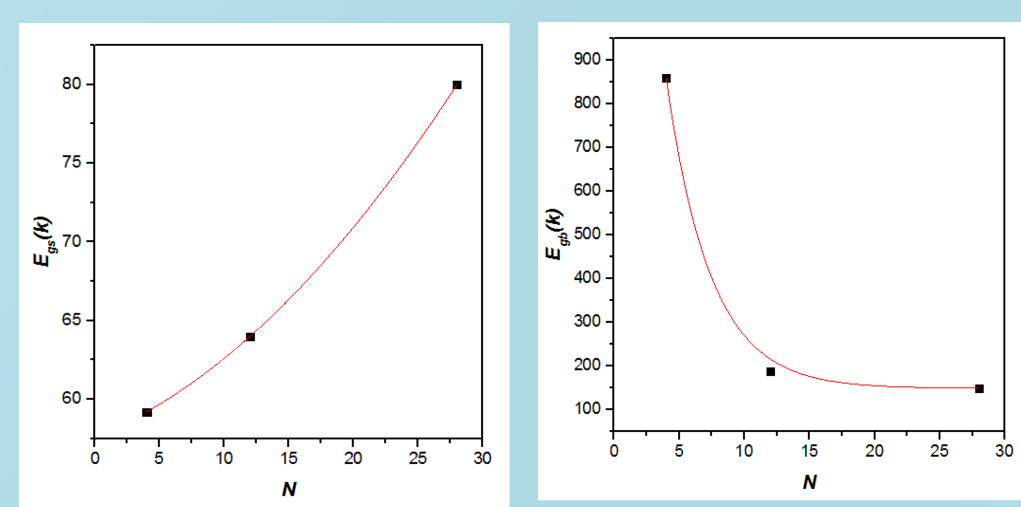

Fig 5 - Variation of Eg(N) as a function of the number of plans N

Conclusions

- **Excitation spectrum shows the existence of *N* Energy modes for *N* planes**
- **The existence of two types of magnon populations created in: volume & area**
- **`Magnétisation varies from T^(3/2) système to trois dimentions**
- **Magnétisation varies in *TlnT* système quasi-bidimentiennels**
- **The effect of the variation of the surface anisotropy α is much more effective for magnons created on the surface.**

Reference

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[3] Qachaou, A., Mehdioui, M., Labyad, N. A., Fahmi, A., Lharch, M. (2019). Effect of Chemical Composition on Volume and Surface Magnon Creation in Multilayer Co x Pt 1 x/Pt. Journal of Superconductivity and Novel Magnetism, 32(3), 667-676