On magnetic multilayers of finite stacking

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A commonly used model of magnetic multilayers, namely the linear chain of classical spins is reconsidered in the zero anisotropy limit. Numerical minimisation of the Heisenberg energy functional shows that the often neglected effects due to the finiteness of the number of magnetically coupled layers result in a variety of fascinating spin configurations. Zero anisotropy minimum energy spin configurations are applied to fitting synchrotron Mössbauer reflectometric spectra of a [$^{57}Fe/FeSi]_{10}$ multilayer on an amorphous substrate. Our results are in favor of loose interlayer coupling of the Fe layer closest to the substrate.

Magnetic multilayers (MMLs) exhibit rich and varied magnetic properties not found in bulk magnetic materials. Examples of such are oscillatory ferromagnetic (FM) and antiferromagnetic (AF) interlayer coupling between magnetic layers separated by non-magnetic spacers and giant magnetoresistance of AF-coupled MMLs. Beside the most commonly discussed FM and AF *bilinear* coupling[1] (the leading term of a trigonometric series), second-order *biquadratic* coupling, preferring 90 degree alignment of neighboring spins was found experimentally in a number of MML systems, like Fe/Cr [2] and Fe/FeSi [3]. In MMLs, the interlayer coupling is weak compared to the strong effective exchange coupling between ionic spins within a given magnetic layer thus we may model the magnetic structure of a MML by representing each magnetic layer as a large classical spin M_i. The model classical spins then interact by the interlayer exchange, experiencing magneto-crystalline anisotropy, too. MMLs are, therefore, physical representations of one-dimensional lines of classical spins. Theoretical treatment of such spin chains often neglect the effects stemming from the *finiteness* of the number of the layers. This latter effect is considered here numerically [4] in the zero magneto-crystalline anisotropy limit and applied to the interpretation of synchrotron Mössbauer reflectomeric time spectra of an [Fe/FeSi]x10 MML on Zerodur glass.

Let us consider a MML consisting of n magnetic (e.g. Fe) and n spacer (e.g. B2-FeSi) layers. The role of the spacers in the model will be limited to mediating the coupling between adjacent Fe spins. Spins are deemed to lay within the plane of the MML film[1]. Now apply a Heisenberg-type localised spin model with molecular field approximation at zero temperature. The model functional of energy per unit area is:

$$\mathcal{E}\left(H\right)=-J\sum_{i=0}^{n-2}\cos\left(\vartheta_i-\vartheta_{i+1}\right)-HM\sum_{i=0}^{n-1}\cos\vartheta_i \tag{1}$$

[1] Due to the shape anisotropy, this is often the case in thin films.

H and M being the magnitude of the external magnetic field, and the layer magnetisation per unit area, respectively, ϑ_i the angle between $\mathbf{H}$ and the magnetisation of the i-th layer ($i = 0, 1, \ldots n-1$) and J is the interlayer coupling coefficient (energy/unit area). For AF coupling $J < 0$. A schematic view of the MML with the corresponding physical quantities is given in Fig. 1. In Eq. (1) $\mathbf{H}$ is taken parallel to the x axis.

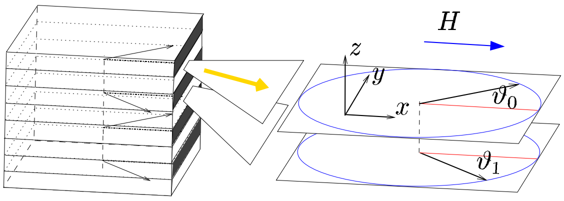

Figure 1: Schematic view of a MML. The light-edged metallic layers are coupled trough the non-metallic (dark-edged) layers. All layer magnetisation vectors lay within the $x-y$ plane. The external field $\mathbf{H}$ is parallel to the x axis.

In the infinite stacking limit the solution of Eq. (1) is a uniformly canted (two-sublattice) state: $\vartheta_i = (-1)^i \vartheta$, and the energy minimum is found analytically. The total magnetisation of the system, M_t is a linear function of the external field:

$$M_t(H) = M \sum_{i=0}^{n-1} \cos\vartheta_i = H \frac{nM^2}{4|J|}. \tag{2}$$

Introducing the reduced magnetic field and reduced magnetisation, $p = \frac{HM}{4|J|}$ and M_r, respectively, one gets:

$$M_r \equiv \frac{M_t(H)}{M_s} = \frac{M_t(H)}{nM} = p. \tag{3}$$

Here M_s is the saturation magnetisation. From Eq. (3) and the definition of p follows that M_s ($M_r = 1$) is reached at $p = 1$. Increasing p above 1, the magnetisation of the system does not increase any further.

In the finite stacking case, however, quite different scenarios occur. The two outermost spins in the stacking have only one neighbour rather than two, therefore those contribute to the total energy by only half of the contribution of the other spins. This fact has little influence on the total magnetisation which will only slightly exceed that of the infinite stacking case. However, the individual spin orientations may considerably differ. In low magnetic fields, as pointed out by Nörtemann *et al*[5], due to the new degrees of freedom, a global state exits (the so called "nonuniform canting region") with energy lower than the uniformly canted two-sublattice solution (cf. Eq. (3) and Fig. 2).

The magnetic structure of a Zerodur/^{57}[Fe/FeSi]$_{10}$ multilayer was studied by synchrotron Mössbauer reflectometry (SMR)[6][2], a technique very sensitive to the *individual* layer magnetisation directions. The B2-FeSi spacer is known to mediate non-oscillatory antiferromagnetic coupling[9] between the Fe layers. SMR spectra of

[2] A review on SMR in materials science has recently been published[7] and some aspects of the method are described in another paper of this proceedings[8].

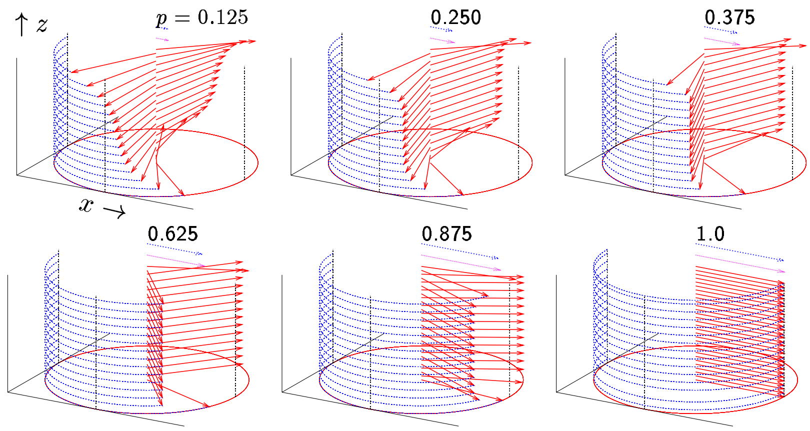

Figure 2: Behaviour of a 30 layer MML of *finite* stacking in external field. The length of the top and next to the top arrows are proportional to p and M_r, respectively. The other arrows visualise the magnetisations of the sub-layers. In zero external field (not shown) an antiparallel, in small external fields a globally twisted structure is observed. Increasing the field the magnetisations approach the uniformly canted structure.

a $^{57}[Fe/FeSi]_{10}$ multilayer were interpreted [6] in terms of a model structure consisting of an upper *two-sublattice* antiferromagnetic block loosely coupled to a ferromagnetic bottom block of Fe layers ("8+2 model"). We have recently shown[10] that a somewhat different interpretation is offered by the present model of finite stacking. Indeed, as shown in Fig. 3, the SMR spectra calculated by assuming an upper 9-layer *finite* block and an *uncoupled* bottom single FM layer block ("9+1 model") yield a better agreement between data and theory. The basic message of the results, namely the appearent decoupling of the Fe layer closest to the substrate remains valid, however.

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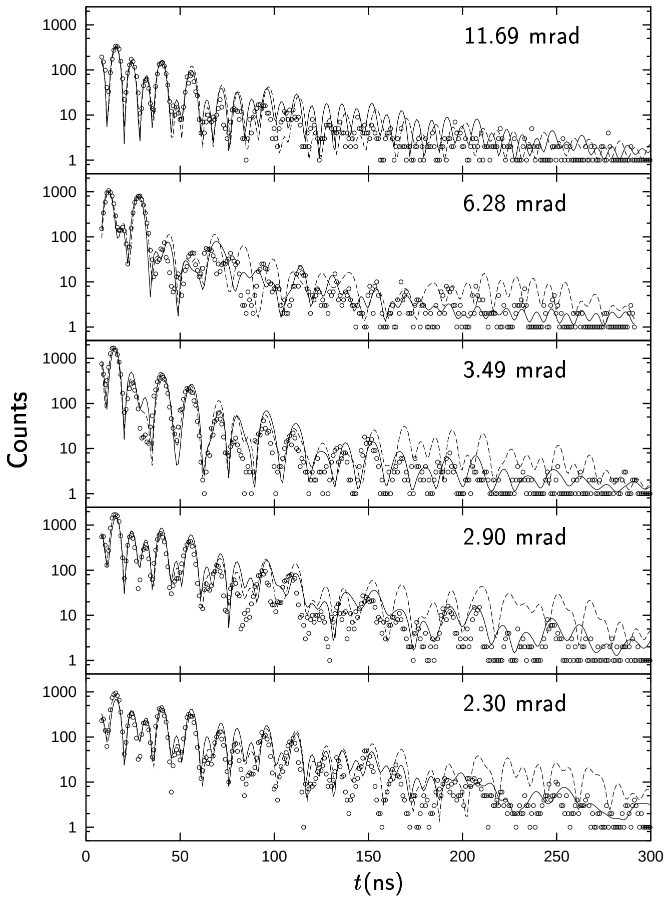

Figure 3: Zerodur/[^{57}Fe/FeSi]$_{10}$ MML SMR time spectra in $H = 0.05$ T external magnetic field at different angles of grazing incidence. The solid and dashed lines are fits corresponding to the "9+1" and the "8+2" models, respectively.

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