

## NUCLEAR MAGNETIC RESONANCE OF $^{57}\text{Fe}$ FROM MAGNETIC DOMAINS AND WALLS IN YTTRIUM IRON GARNET

K. Kouřil, J. Kohout, H. Štěpánková<sup>1</sup>, J. Englich, V. Chlan

Faculty of Mathematics and Physics, Charles University,  
V Holešovičkách 2, 18000 Praha 8, Czech Republic

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We present an NMR study of hyperfine fields at  $^{57}\text{Fe}$  nuclei in polycrystalline yttrium iron garnet. We measured spectra of  $^{57}\text{Fe}$  nuclei situated in tetrahedral and octahedral sites in magnetic domains as well as in domain walls at several temperatures within the range of 4.2–344 K. Comparing the simulated lineshapes to the experimental ones we found that the main contribution to the observed spectra from walls originated from nuclei in  $70.5^\circ$  Bloch walls.

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### 1 Introduction

Yttrium iron garnet  $\text{Y}_3\text{Fe}_5\text{O}_{12}$  (YIG) is a prominent magnetic material studied for its applications as well as for fundamental physical properties. It is a collinear ferrimagnet ( $T_c \sim 560$  K) of cubic structure with an easy magnetization axis in a direction of  $\langle 111 \rangle$  type [1]. Its two magnetic sublattices are formed by ferric ions in octahedral  $a$  sites (site symmetry axis  $S_4$  in a direction of  $\langle 111 \rangle$  type) and tetrahedral  $d$  sites (site symmetry axis  $S_4$  in a direction of  $\langle 100 \rangle$  type).

YIG was successfully studied by means of hyperfine methods. In particular  $^{57}\text{Fe}$  nuclear magnetic resonance (NMR) was benefiting because of its good resolution when employed to determine temperature dependences of sublattice magnetizations [2] or to identify cationic impurities and defects [3]. For those applications it was convenient to detect the NMR signal from nuclei inside magnetic domains. In this paper we primarily deal with NMR at  $^{57}\text{Fe}$  nuclei of ferric ions situated inside domain walls with the aim to compare experimental and simulated spectral lines.

### 2 Experiment

The studied sample was a bulk polycrystalline YIG prepared by ceramic technique. We measured  $^{57}\text{Fe}$  NMR spectra of nuclei in  $a$  and  $d$  sites in domains and in domain walls at several temperatures within a range of 4.2–344 K. Measurements were carried out with a coherent pulse NMR spectrometer in zero external magnetic field.

<sup>1</sup>E-mail address: helena.stepankova@mff.cuni.cz

Radiofrequency (rf) fields at resonating nuclei in magnetic materials are strongly amplified by electron magnetization oscillations [4]. Mechanisms of the enhancement differ for nuclei in domains and in walls, which often results in a large difference of corresponding multiplying enhancement factors  $\eta$ . In our sample,  $\eta$  in domains was by two orders lower than that in walls. It allowed us to separate NMR signals from domains and walls by adjusting the rf pulse amplitude.

The  $^{57}\text{Fe}$  spectra recorded from domains at 4.2 K consisted of a single line at 64.96 MHz (halfwidth  $\sim 30$  kHz) assigned to  $d$  sites and of two lines at 75.05 and 76.05 MHz (halfwidths  $\sim 10$  kHz and 30 kHz) corresponding to  $a$  sites. Spectra from walls were formed by broad lines of complicated shape (Fig. 1, 2). We did not observe any significant qualitative changes of the lineshapes with increasing temperature (except for frequency shifts and a decreased signal/noise ratio).

### 3 Simulation of NMR spectra from domain walls

NMR spectra of nuclei from domain walls are determined by many factors. The dominating one is a resonant frequency anisotropy, i.e. a dependence of the resonant frequency  $f$  on a magnetization direction. It can be written as

$$f = I + \mathbf{n}\mathbb{A}\mathbf{n}, \quad (1)$$

where  $I$  denotes an isotropic term,  $\mathbf{n}$  is a unit vector in a direction of magnetization and  $\mathbb{A}$  is a symmetric traceless tensor. For the nuclei in  $a$  sites having their local symmetry axis along [111] and for those in  $d$  sites with their local symmetry axis along [100], respectively, the anisotropy tensors are expressed as

$$\mathbb{A}_a = A_a \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix}, \quad \mathbb{A}_d = A_d \begin{pmatrix} -2 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (2)$$

Isotropic terms  $I_a = 75.809$  MHz,  $I_d = 64.961$  MHz and anisotropy parameter  $A_a = -373$  kHz at  $T = 4.2$  K were determined from experimental domain spectra,  $A_d = 46$  kHz was taken from [5].

The sites within a sublattice are not magnetically equivalent because they differ in the orientation of their site symmetry axes. Since there are three possible orientations of the  $d$  site symmetry axis and four orientations of the  $a$  site symmetry axis in a unit cell, there are three and four groups of magnetically equivalent sites for  $d$  and  $a$  sublattice, respectively. The anisotropy tensors for the sites belonging to the other groups can be obtained from the listed ones (eq. 2) using operations of crystal symmetry [5].

Our simulation of the domain wall spectra is based on an assumption that mainly Bloch walls are present in the sample. Because of easy directions one can expect  $70.5^\circ$ ,  $109.5^\circ$  or  $180^\circ$  Bloch walls. To estimate a direction of magnetization at a given position within a domain wall we presumed that magnetization orientation  $\mathbf{n}$  inside the wall depends only on a coordinate  $\zeta$  on an axis perpendicular to the wall plane. Because the magnetization in a Bloch wall is in-plane, we can specify its direction by an angle  $\alpha$  between the vector  $\mathbf{n}$  and the magnetization in one of the adjacent domains.

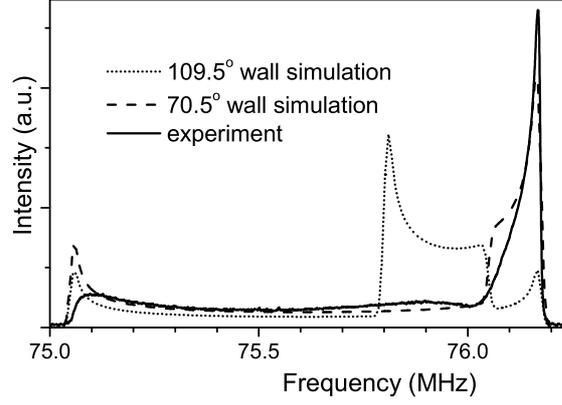


Fig. 1. Simulated and experimental ( $T=4.2$  K) domain wall spectra of  $^{57}\text{Fe}$  nuclei in YIG,  $a$  sites.

An increase in the energy (compared to the domain) related to the unit wall area and an increment  $d\zeta$  at a position  $\zeta$  was described as a sum of two terms: an increase of a cubic magnetocrystalline anisotropy energy  $E_A(\alpha(\zeta))d\zeta$  and an increase of an exchange energy  $E_E(\alpha(\zeta)) = J_{eff}(d\alpha/d\zeta)^2d\zeta$ , where  $J_{eff}$  is an effective exchange parameter. By minimizing the total wall energy a differential equation was obtained

$$\frac{d\alpha}{d\zeta} = \sqrt{\frac{E_A(\alpha)}{J_{eff}}}. \quad (3)$$

The excitation rf pulse as well as the detected NMR signal are enhanced by an effect of a domain wall motion. For the corresponding enhancement factor  $\eta$  we can write [4]

$$\eta = c \frac{\partial \alpha}{\partial \zeta}, \quad (4)$$

where  $c$  is a constant given by the domain wall mobility.

The contribution to the spectral intensity from nuclei in the  $k$ th group of magnetically equivalent sites resonating at a frequency  $f_k$  can be expressed as

$$I_k \sim \left| \frac{df_k(\alpha(\zeta))}{d\zeta} \right|^{-1} \cdot \eta(\alpha). \quad (5)$$

The first term reflects the proportionality to the number of resonating nuclei and the second term describes the amplification of detected signal by domain wall oscillations. In this formula differences in the excitation conditions and in spin-spin relaxation times within the wall were not taken into account. Expressing the derivative in the first term using eq. (4) yields

$$I_k \sim c \left| \frac{df_k(\alpha)}{d\alpha} \right|^{-1}. \quad (6)$$

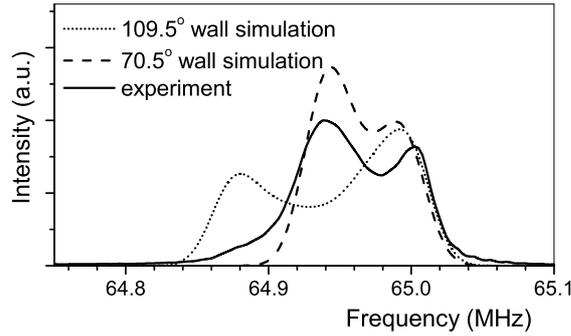


Fig. 2. Simulated and experimental ( $T=4.2$  K) domain wall spectra of  $^{57}\text{Fe}$  nuclei in YIG,  $d$  sites.

We evaluated the intensities for each sublattice as a sum of contributions from all the groups of magnetically equivalent sites, i.e.  $I = \sum_k I_k$ . Finally we calculated a convolution of this intensity with a Gaussian function with the same halfwidth as main spectral lines from domains in order to reflect nonzero homogeneous linewidth.

The simulations were performed for  $70.5^\circ$  and  $109.5^\circ$  Bloch walls. We did not simulate spectra of a  $180^\circ$  wall as this type is energetically inefficient. Both the simulated and experimental spectra for  $T = 4.2$  K normalized to a unit area are shown in Figs. 1 and 2.

#### 4 Conclusions

From the comparison of the experimental and simulated spectra we deduced that the observed domain wall spectra in a bulk YIG polycrystalline sample originated predominately from nuclei in  $70.5^\circ$  Bloch walls. Despite the very simple model we used, the simulated spectra qualitatively well conformed to the experimental ones. If we assume that integral intensities of NMR spectra per unit wall area are comparable for the considered wall types, we can conclude that the major type of domain walls present in the studied sample is the  $70.5^\circ$  Bloch wall. The reason is probably its lower energy: in our model this wall has the least energy per unit area.

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