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THE COMPARATIVE NMR STUDY OF DOMAIN WALL PINNING AND MOBILITY IN MAGNETS UNDER THE ACTION OF AN ADDITIONAL MAGNETIC VIDEO-PULSE

Grigor Mamniashvili, T.O.Gegechkori, G.P.Ivanov, G.J.Donadze

Andronikashvili Institute of Physics of the I. Javakhishvili Tbilisi State University,

Abstract

A comparative study of the pinning and mobility of domain walls in cobalt nano-and micropowders and lithium ferrite has been carried out under the action of a magnetic video-pulse applied between two radio-frequency pulses on the two-pulse echo and in the case of the combined action of the magnetic video-pulse and radio-frequency pulse, leading to the formation of a stimulated magnetic echo. A correlation is shown between the results of determining the pinning force and domain walls mobility by these two methods, which allows one to use these alternative methods for measuring the domain wall pinning force and mobility in magnets.

Keywords*: nuclear spin echo, magnetic video-pulse, lithium ferrite, cobalt, domain wall mobility, pinning*

1. Introduction

In [1-4], different methods of NMR nuclear echo-spectroscopy were used to study the properties of magnetically ordered substances.

Among them, we note the observation of a nuclear spin echo in magnets in the presence of additional magnetic video-pulse (MVP) to study the pinning of domain walls (DWs) in bulk magnets and nanosystems (nanoparticles and nanowires). The physical principle underlying this method is based on the fact that when observing a nuclear spin echo from nuclei located in DWs, they can be easily controlled when exposed to the additional MVP field.

In particular, in [5-6], it was shown that the use of nuclear spin echo of nuclei in DWs of lithium ferrite and cobalt nanowires in combination with MVP is a convenient technique for studying the pinning of DWs in these systems. This method is of great interest for the study of magnets for applications in information recording devices and sensors.

In [7] it was studied the action of MVP affecting the nuclear spin echo signal in lithium ferrite. The effects of suppression and restoration of echo signals were observed when using MVP pulses of different polarity.

The dependence of the MVP echo suppression effect on the external steady magnetic field was investigated, indicating that the observed phenomena were associated with DWs.

For the first time, the dynamics of DW in a single-crystal ferrite sample grown under the MVP action were studied by Galt [8].

It was shown that the dynamics of the DW is described by the linear dependence of the DW velocity υ on the applied MVP:

$$\upsilon = S(H - H_o), \qquad (1)$$

where S is the mobility of the DW, and H_o is the critical field below which the DW is pinned (fixed).

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The aim of this work is a comparative NMR study with additional MVP of the DW pinning in cobalt micro-and nanopowders and lithium ferrite. The suppression of the echo signal caused by the movement of the DW under the influence of MVP fields was investigated.

Interest in NMR studies of lithium ferrite is stimulated by a number of features of its crystal and magnetic structures, including the ordered arrangement of ions in octahedral sites [9]. In addition, lithium ferrite is promising as a working substance in the RF pulse processors based on the nuclear spin echo phenomenon [10]. The interest in this magnet is also due to the fact that, among the known polycrystalline magnetic materials, this substance has the highest values of the transverse relaxation time T_2 both at low and at room temperatures.

It should be noted that in magnetic crystals with high DW mobility, an alternating magnetic field practically does not penetrate into domains (by analogy with the skin effect in metals). Thus, one practically observes the NMR signals not from the domain nuclei, but from the nuclei arranged in the DWs of magnetic materials under the present study.

2. Experimental results and their discussion

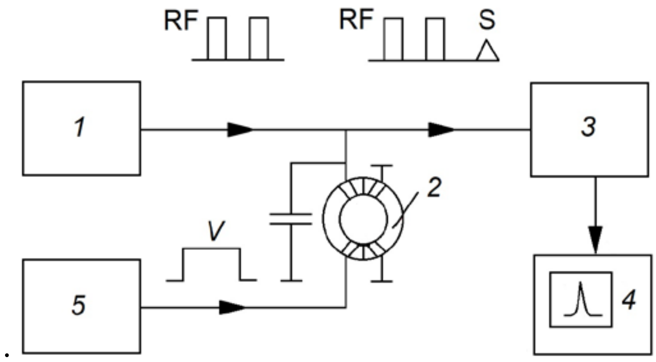

Fig. 1.

Block diagram of the experimental setup: 1 - RF pulse excitation generator; 2 - resonator with a ring-shaped sample of lithium ferrite; 3 - receiver; 4 - oscilloscope; 5 - channel of MVP formation.

MVP action on The block diagram of the experimental setup for NMR study of lithium ferrite with additional MVP action is shown in Fig. 1: RF excitation pulses are generated by generator *1*. Next, a sequence of NMR excitation echo pulses enters the resonator *2* with the ring-shaped sample of lithium ferrite used. The RF field of the pulses excites the echo signal in the upper coil of the resonator *2*. Then these pulses, together with the echo signal S, enter the receiver *3* and are recorded by the oscilloscope. Channel *5* generates additional MVP pulses to the lower winding of the resonator. A detailed description of the NMR spectrometer and the MVP for NMR experiments in cobalt is given in [6]. The experimental results were obtained at T = 77. The echo signal amplitude was measured in the presence and without of MVP.

We used samples of lithium-zinc ferrite $Li_{0.5}Fe_{1.0}Zn_{0.15}O_4$, which were rings with a diameter of 12–15 mm and a weight of 5–8 g, enriched in the ^{57}Fe isotope to 96.8% in order to increase the intensity of the echo signal, which were produced by means of a conventional ceramic preparation technique with the ^{57}Fe iron isotope enrichment. It was studied also cobalt microparticles were obtained by inductive melting and filed to powder with an average grain size less than 50 μ and carbon nanopowders doped with cobalt nanoclusters with an average size of 50 nm [6].

Since the external RF field acts on the nuclei through the electronic magnetic moments M, let us consider the motion of electronic magnetization in the DWs under the action of the MVP. DW displacements, even being insignificant, can be accompanied by a large rotation of M. In this case the rotation of M inside the DW is proportional to the displacement of the DW. This process is accompanied by a change in the local hyperfine field (HFF) on nuclei due to the anisotropy of the HFF in cobalt [11] and RF gain factors η [1] proportional to DW displacements. The MVP amplitude H_o at which the two-pulse echo (TPE) intensity begins to decrease, associated with the

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onset of the DW motion is naturally related to the pinning force H_o. In Fig. 2 results of polycrystalline cobalt, samples are shown recorded along the NMR spectrum when an MVP was placed in between RF pulses in the face-centered cubic (FCC) phase of cobalt.

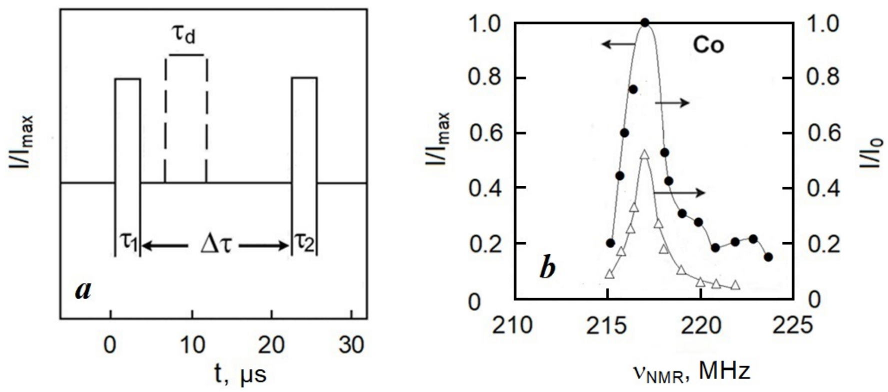

Fig. 2

(a) location of the MVP relative to the RF pulses; (b) I/I_{max} - NMR intensity spectrum of FCC cobalt (●). I/I_o - normalized NMR intensity spectrum under the MVP influence.

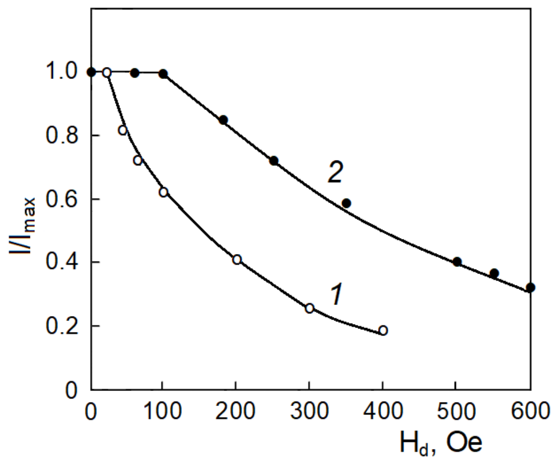

Fig. 3.

Dependences of the echo intensities on the amplitude of the magnetic videopulse in the case of cobalt micropowder (1) (o) and cobalt nanoclasters (2) (•), [6].

Under the effect of MVP on the echo signal, its attenuation is associated with the anisotropy of HFF, which violates the phase coherence of precessing nuclear spins and, accordingly, reduces the efficiency of the rephasing process [6].

The anisotropy of HFF is especially pronounced in Co, which has a much higher HFF anisotropy as compared to lithium ferrite. Therefore, the effect of MVP in cobalt is most effective with the asymmetric action of MVP, in contrast to lithium ferrite possessing an order of magnitude lower value of HFF anisotropy [10]. But, instead, lithium ferrite is characterized by much higher values of its DW mobility due to the fact that η factor in lithium ferrite is about $\eta \sim 2\ 10^5$ as compared with only $\eta \sim 100$ in cobalt.

Due to the lower mobility of DWs in Co, the echo signal is much less suppressed by MVP action as compared with lithium ferrite. For this reason, the pinning field in cobalt is much higher compared with it in lithium ferrite. Its value in Co was previously estimated by the method of combined action of RF and MVP, based on the appearance of an additional stimulated magnetic echo (ME) signal. It was supposed that ME emergence is caused by the displacement of DWs under the influence of MVP [6]. The ME arises as a result of abrupt changes in the effective magnetic field H_{eff} in a rotating coordinate system (RCS) due to a rapid nonadiabatic change in the direction of H_{eff} when the position of the nucleus in the DW changes with its displacement by the MVP and, consequently, the associated changes in the HFF and factor η, when the MVP amplitude exceeds a threshold pinning value H_o. Fig. 4 shows the dependences of the intensity of the stimulated ME formed by the MVP and the two edges of the RF pulse in analogy with three-pulse stimulated Hahn echo [1].

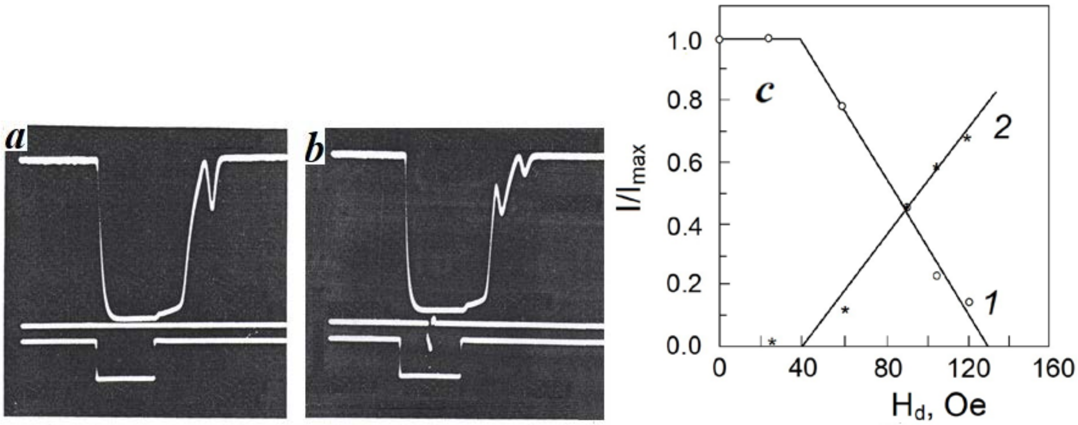

Fig. 4.

(a) Oscillogram of a single-pulse echo (SPE) on the upper beam on the right; (b) oscillogram of a stimulated magnetic echo (ME) in cobalt, formed by an MVP and two edges of the RF pulse, formed before an SPE signal. The middle beam shows the location and duration of the MVP. The lower beam represents the RF pulse: ν_{NMR} = 216 MHz, τ = 18 μs, T = 77 K; (c) dependences of the echo signal intensity in cobalt on the amplitude of the magnetic pulse, ν_{NMR} = 216 MHz, τ = 22 μs, τ = 0.5 μs, T = 77 K in cobalt: 1 - single-pulse echo; 2 - stimulated magnetic echo (ME) generated by the action of MVP and the edges of the RF pulse.

It is of interest to establish the form of the corresponding diagrams of the effect of MVP on the TPE in lithium ferrite in connection with the much lower values of its HFF anisotropy and higher mobility of DWs. As shown in [9], the NMR spectrum of lithium ferrite at T=77 K consists of two well-resolved lines, where the low-frequency line belongs to the tetrahedral A sites, and the high-frequency line to the octahedral B sites, Fig. 5*a*.

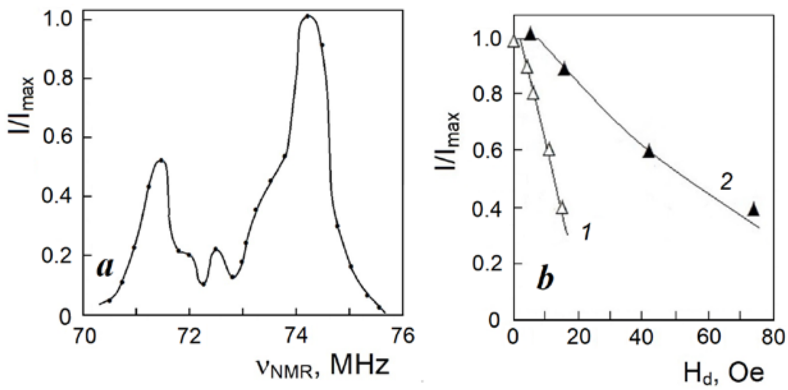

Fig. 5.

(a) ^{57}Fe NMR signal spectrum in lithium-zinc ferrite; (b) Dependences of the echo signal intensity in lithium-zinc ferrite on the amplitude of the magnetic video-pulse on NMR frequencies 71 and 74 MHz, curves 1 and 2, correspondingly, MVP duration τ_d = 0.5 μs, T = 77 K.

Analysis of the dependence of the effect of MVP on echo signals in the studied samples shows a significant, up to one order of magnitude increase in the mobility of DWs and decrease in the pinning force in lithium ferrite in comparison with cobalt. A particularly large effect of MVP is observed for the echo signal from nuclei located in octahedral B positions of lithium ferrite at a frequency of 74 MHz with more anisotropy of the HFF [9], Fig. 8b, as compared with the echo signal from nuclei in tetrahedral A positions at a frequency of 71 MHz, Fig. 5b.

In lithium ferrite the stimulated ME signals were also observed and studied, Fig. 6, similar to cobalt, Fig. 4.

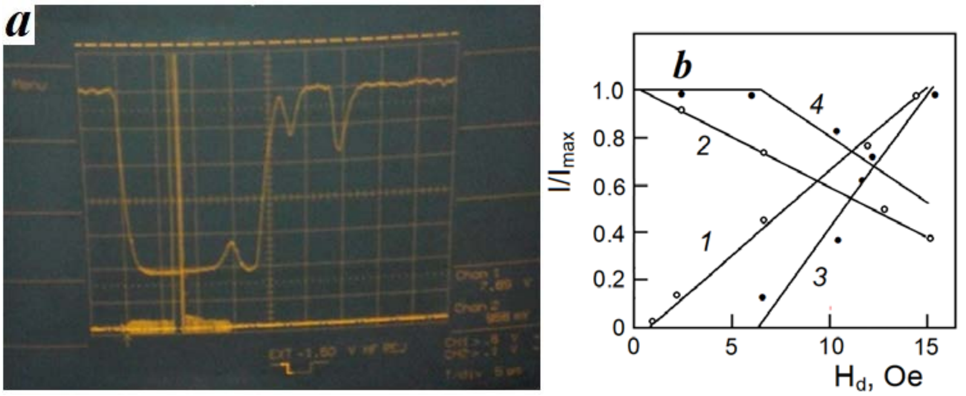

Fig. 6.

(a) Oscillogram of magnetic ME and single-pulse echo SPE signals in lithium-zinc ferrite (upper beam), the lower beam shows the duration of the RF magnetic pulses as well as the amplitude of the magnetic video pulse; (b) dependences of the signals of the magnetic (1,3) and single-pulse (2,4) echoes on the amplitude of the magnetic video pulse at frequencies of 74 and 71 MHz, respectively.

The MVP amplitude at which the magnetic echo appears, Fig. 6*b*, correlates with the MVP amplitude acting on the TPE, at which its decrease begins, associated with the DW pinning field H_o, Fig. 5, which gives an alternative way of measuring the DW pinning field H_o in magnets.

The observed experimental dependences of the signals of the magnetic, SPE, and TPE can be understood taking into account that, according to (1), under the action of the MVP, the DWs reversibly shift by a distance Δx proportional to the amplitude of the MVP: $\Delta x = \upsilon \cdot \tau_d = S(H - H_o)\,\tau_d$ when the MVP amplitude exceeds the value pinning field H_o. In the Δx layer nuclei under the combined action of RF and MVP experience the effect of an abrupt change in magnitude and direction of the effective magnetic field H_{eff} in the rotating coordinate system (RCS) due to the change in local HFF and η, where $H_{eff} = \frac{1}{\gamma_n}(\Delta\omega_j \vec{z} + \omega_1 \vec{y})$ and γ_n is the nuclear gyromagnetic ratio, $\vec{\mathbf{z}}$ and $\vec{\mathbf{y}}$ are the unit vectors in RCS, $\Delta\omega = \omega_{NMR} - \omega_{rf}$ is the detuning for the j-th isochromate, $\omega_1 = \gamma_n \eta H_1$ is the RF magnetic field, H_1 is the pulse amplitude in frequency units and η is the RF field gain factor. Therefore, accordingly to the nonresonant model of SPE formation [6], the action of MVP is equivalent to the effect of a second RF pulse at the formation of a three-pulse stimulated Hahn echo, resulting in the formation of the ME signal.

In this case, its amplitude would be proportional to the number of nuclei in the Δx layer, formed at the displacement of the DW: $I_{ME} \sim \Delta x/L$, where L is the width of the exciting section of the DW under the action of RF pulse. Correspondingly, these nuclei do not contribute to SPE reducing it to $I_{SPE} \sim (L-\Delta x)/L$. In this case, the jump-like change in the nuclear NMR frequencies in RCS must satisfy the condition $\Delta\omega'_j\ \tau_d << 1$, where $\Delta\omega'_j = (\Delta\omega^2 + \omega_1^2)^{1/2}$, or in other words the precession period of nuclei in RCS should be much larger as compared with τ_d. Under the action of MVP on the TPE in the time interval between RF pulses, the RF is absent and nuclei are precessing in a local HFF with frequencies $\omega_j = \gamma_n\ H_{HFF}$ and it should be fulfilled the condition $\omega_j\ \tau_d << 1$, requiring a nanosecond duration MVP as in case of inverse echo [12] to have additional ME signals. Therefore, the effect of MVP on TPE leads only to a decrease in the intensity I_{TPE} of TPE, proportional to the displacement of the DW : $I_{TPE} \sim (L - \Delta x)/L$, due to the loss of phase coherence

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of the nuclei located in this layer. This model allows us qualitatively understand the obtained experimental dependences of the ME, SPE and TPE signals under the influence of MVP.

3. Conclusion

A comparative study of the pinning of DWs in cobalt and lithium ferrite has been carried out under the action of an MVP applied between two RF pulses on the TPE and in the case of the combined action of the RF and MVP pulses, leading to the formation of a stimulated ME. A correlation is shown between the results of determining the pinning fields using these two alternative methods for measuring the DW pinning in magnets.

References

[1]. Turov E.A., Petrov M.P., “Nuclear magnetic resonance in ferro- and antiferromagnets,” New York: Haisted, 1972.
[2]. Wurmehl S., Kohlhepp J.T. “Nuclear magnetic resonance studies of materials for spintronic applications,” J. Phys. D: Appl. Phys. 2008, Vol. 41, pp. 17300.
[3]. Shmyreva A., Matveev V.V., Yurkov G.Y. “Nuclear magnetic resonance in magnetic nanomaterials as an effective technique to test and/or to certificate local magnetic properties,” Int. J. Nanotechnol. 2016, Vol. 13, pp. 126-135.
[4]. Mamniashvili G., Zviadadze M., Gegechkori T., Shermadini Z. “NMR spectroscopy of magnets using arbitrary number and duration radio-frequency pulses,” International Journal of Trend in Research and Development 2016, Vol. 3, pp. 434-473.
[5]. Pleshakov I.V., Popov P.S., Kuz’min Yu.I., Dudkin D.I. “NMR study of domain wall pinning in a magnetically ordered material,” Tech. Phys. Lett. 2016, Vol. 42, pp. 59-62.
[6]. Gavasheli T.A., Mamniashvili G.I., Shermadini Z.G., Zedginidze T.I., Petriashvili T.G., Gegechkori T.O., Janjalia M.V. “Investigation of the pinning and mobility of domain walls in cobalt micro-and nanowires by the nuclear spin-echo method under the additional influence of a magnetic video pulse,” J. Magn. Magn. Mater. 2020, Vol. 500, pp. 1555310.
[7]. Pleshakov I.V., Klekhta N.S., Kuz’min Yu.I. “The effect of a pulsed magnetic field on the nuclear spin echo signal in ferrite,” Tech. Phys. Lett. 2012, Vol. 38, pp. 853-855.
[8]. Galt J.K., “Motion of individual domain walls in a nickel-iron ferrite,” Bell Syst. Tech. J. 1954, Vol. 33, pp. 1023-1054.
[9]. Doroshev V.D., Klochan V.A., Kovtun N.M., Seleznev V.N. “The effect of dipole and anisotropic hyperfine fields on NMR of Fe^{57} in lithium ferrite $Li_{0.5}Fe_{2,5}O_4$,” Phys. Status Solidi A, 1972, Vol. 9, pp. 679-689.
[10] Pleshakov I.V., Popov P.S., Dudkin V.I., Kuz’min Y.I. “Spin echo processor in functional electronic devices: Control of responses in the processing of multipulse trains,” J. Commun. Technol. Electron. 2017, Vol. 62, pp. 583-587.
[10]. Galt J.K., “Motion of individual domain walls in a nickel-iron ferrite,” Bell Syst. Tech. J. 1954, Vol. 33, pp. 1023-1054.
[11]. Searle C.W., Kunke H.P.l, Kupca S., Maartense I. “NMR enhancement of a modulating field due to the anisotropic component of the hyperfine field in hcp Co and YCo_5,” Phys. Rev. B. 1977, Vol. 15. pp. 3305-3308.
[12]. Ignatchenko V.A., Mal'tsev V.K., Reihgardt A.E., Tsifrinovich V.I. “New mechanism for the formation of nuclear spin echo,” JETP Letters, 1983, Vol. 37, No. 9, pp. 520-522.

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