1/f magnetic noise in exotic $\varepsilon$-In$_{0.24}$Fe$_{1.76}$O$_3$ nanoparticles

S A Kostyuchenko$^1$ and A I Dmitriev$^2$

$^1$ Lomonosov Moscow State University, Moscow, 119992, Russia
$^2$ Institute of Problems of Chemical Physics of Russian Academy of Sciences, Chernogolovka, 142432 Russia

E-mail: aid@icp.ac.ru

Abstract. The relation between the magnetic viscosity of exotic $\varepsilon$-In$_{0.24}$Fe$_{1.76}$O$_3$ nanoparticles and 1/f magnetic noise caused by the random thermally activated magnetization reversal of a single nanoparticle was found.

1. Introduction

The physics of magnetic noises is still an intriguing fundamental field of science. Magnetic noises manifest in the logarithmic dependence of slow magnetization reversal (magnetic viscosity) in different magnets [1–5]. The general concept of the logarithmic magnetization reversal as a consequence of a uniform energy barrier distribution $F(E)$ was developed in [6]. In the case of thermally activated processes, there exists a direct relation between an $F(E)$ distribution and a relaxation time distribution $F(\tau)$, which determines the spectrum of magnetic fluctuations [7]. The key characteristic of noise is spectral density $W(f)$, which characterizes the distribution of the random signal power over a frequency spectrum $f$. If $W(f) = $ const, the noise is called “white”. In contrast to the noise having a spectrum $W(f) = $ const, the origin of flicker noise with a spectrum $W(f) \sim 1/f$ is poorly understood. Complex methods of detecting electric noise 1/f in thin films, heterostructures, and monoatomic graphene layers are being developed [8]. However, the physics of the magnetic 1/f noises is still retained beyond the scope of investigation. In this work, we study the slow relaxation of the magnetization of $\varepsilon$-In$_{0.24}$Fe$_{1.76}$O$_3$ nanoparticles ensembles. New nanomagnets based on the epsilon phase of iron oxide $\varepsilon$-Fe$_2$O$_3$ demonstrate a giant (up to 2.34 T) coercive force and magnetic anisotropy [9]. In addition, the $\varepsilon$-Fe$_2$O$_3$ phase exhibits magnetoelectric properties [10] and is known to be a good absorber of millimetre electromagnetic waves [11]. Magnetic properties of $\varepsilon$-In$_{0.24}$Fe$_{1.76}$O$_3$ nanoparticles ensembles were well studied in papers [12–14]. The aim of the study is to find the relation between the magnetic viscosity of $\varepsilon$-In$_{0.24}$Fe$_{1.76}$O$_3$ nanoparticles and 1/f magnetic noise caused by the random thermally activated magnetization reversal of a single nanoparticle.

2. Experiment

$\varepsilon$-In$_{0.24}$Fe$_{1.76}$O$_3$ nanoparticles with lengths of 80 nm and diameters of 35 nm were synthesized by two methods: synthesis by inverse micelles and the sol-gel method [15, 16]. Nanoparticles were grown in a solution of inverse micelles containing the nitrates of iron and indium. The $\varepsilon$-In$_{0.24}$Fe$_{1.76}$O$_3$ nanoparticles were studied by mass spectrometry, transmission electron microscopy, and x-ray diffraction [15, 16]. The nanoparticles had an orthorhombic crystal structure with four nonequivalent cation positions for the Fe ion. One of these has tetrahedral surroundings and the other three, octahedral ones. The indium ions are a substitution impurity and align themselves in octahedral iron ion sites. Time dependences of the magnetization $m(t)$ of samples were measured using a SQUID...
magnetometer MPMS 5XL Quantum Design. The sample was first magnetized in a magnetic field \( H = 50 \) kOe (exceeding the strength of the saturation field). The time of exposure of the sample to this magnetic field was 300 s. Following such treatment, the field directed opposite to the magnetic moment vector of the sample was switched on. The time of field reversal was approximately 90 s. After the reverse magnetic field was set, the time dependence of the magnetic moment was measured during 3400 s.

3. Experimental results

Figure 1 shows the magnetization increment dependences \( \Delta m(t) \) at temperature \( T = 300 \) K in different magnetic fields directed opposite to the magnetic moment vector of the sample on a logarithmic time scale.

It can be seen from figure 1 that \( \Delta m(t) \) is straightened in semi-logarithmic coordinates. The tangent of the slope of \( \Delta m(\ln t) \) dependences corresponds to magnetic viscosity \( S = \frac{d\Delta m}{d(\ln t)} \). The solid lines represent the result of approximation with the following expression:

\[
\Delta m(t) \sim S \ln t.
\]  

Slopes of \( \Delta m(\ln t) \) curves and corresponding magnetic viscosities are non-monotonic functions of magnetic field (figure 1). Field dependences \( S(H) \) at \( T = 300 \) K show maximums corresponding to 8 kOe (figure 2).

4. Discussion

4.1. Time dependences of magnetization. Magnetic viscosity

When the relaxation process caused by fluctuations is characterized by a single value of time \( \tau \), the time dependence of the magnetization \( m(t) \) is described by the exponential function [6]:

\[
m(t) = m_0 \exp \left( -\frac{t}{\tau} \right).
\]

Actually, thermal activated fluctuations are characterized by a wide relaxation time distribution \( F(\tau) \) density [6]:

\[
F(\tau) = \frac{k_B T}{\tau(E_2 - E_1)}.
\]
where $E_2 - E_1$ – the range of activation energy of fluctuations. In this case, we have the expression:

$$m(t) = m_0 \frac{k_B T}{E_2 - E_1} \int_0^\tau \exp\left(-\frac{t}{\tau}\right) \frac{1}{\tau} d\tau.$$  \hspace{1cm} (4)

From Equation (4) we obtain the expression for the magnetization increment:

$$\Delta m(t) \sim \frac{k_B T}{E_2 - E_1} \ln t.$$ \hspace{1cm} (5)

When comparing Equation (5) with Equation (1) (which was used to describe the experimental $\Delta m(t)$ dependences), we can derive a formula to calculate magnetic viscosity $S$ expressed in the units of initial magnetization in a given magnetic field:

$$S = \frac{k_B T}{E_2 - E_1}.$$ \hspace{1cm} (6)

Thus, the logarithmic kinetics of the spontaneous magnetization reversal of the $\varepsilon$-In$_{0.24}$Fe$_{1.76}$O$_3$ nanoparticles is determined by the superposition of relaxation processes with a wide relaxation time distribution.

4.2. Spectral density of thermal fluctuations. Relation between Magnetic Viscosity and Magnetic Noise

When the relaxation process is characterized by a single value of time $\tau$, the normalized spectral density of magnetic fluctuations is described by the Lorentz function:

$$W(f) = \frac{2\tau}{1 + (2\pi \tau)^2}.$$ \hspace{1cm} (7)

On the assumption of a wide relaxation time distribution $F(\tau)$ (see Equation (3)), the spectral density is found by integrating Equation (7):

$$W(f) = \frac{k_B T}{E_2 - E_1} \int_0^\tau \frac{\tau}{1 + (2\pi \tau)^2} \frac{1}{\tau} d\tau = \frac{k_B T}{2(2\pi f)^2}.$$ \hspace{1cm} (8)

Equation (8) determines the spectral density of flicker noise. Thus, $1/f$ noise is formed as a superposition of Lorentz spectra [17, 18]. When comparing Equations (8) and (6), we can find a relation between the magnetic viscosity and the spectral density of thermal fluctuations:

$$W(f) = \frac{S}{2f}.$$ \hspace{1cm} (9)

Figure 2 shows the $W(f)$ dependences of the magnetic fluctuation spectrum that determines the kinetics of spontaneous magnetization reversal of the samples shown in figure 1 that were calculated by Equation (9). The envelopes of the spectral dependence curves correspond to the field dependence of the magnetic viscosity $S(H)$. Thus, when controlling the magnetic viscosity by changing the magnetic field, we change the “window” width of detecting a magnetic fluctuation spectrum.
5. Summary
The logarithmic kinetics of the magnetic viscosity in exotic ε-In$_{0.24}$Fe$_{1.76}$O$_3$ nanoparticles is determined by the superposition of thermally activated magnetization reversal of a single nanoparticle with a wide relaxation time distribution. A relation between the magnetic viscosity and the spectral characteristics of magnetic fluctuations in nanoparticles ensembles was found.

Acknowledgments
Authors are grateful to R B Morgunov for discussion. The work was supported by the Russian Foundation for Basic Research, project no. 16-07-00863 a.

References
[1] Guy C N 1978 J. Phys. F 8 1309
[2] Street R and Woolley J C 1949 Proc. Phys. Soc. A 62 562
[3] Jinfang L, Shuming P, Helie L, Denglu H and Xiangfu N 1991 J. Phys. D 24 384
[4] Collocott S J and Dunlop J B 2008 J. Magn. Magn. Mater. 320 2089
[5] Gaunt P 1986 J. Appl. Phys. 59 4129
[6] Dmitriev A I, Morgunov R B and Zaitsev S V 2011 J. Exp. Theor. Phys. 112 (2) 317
[7] Dutta P and Horn P M 1981 Rev. Mod. Phys. 53 497
[8] Balandin A A 2013 Nature Nanotechnol. 8 549
[9] Ohkoshi S and Tokoro H 2013 Bull. Chem. Soc. Jpn. 86, 897907
[10] Gich M, Frontera C, Roig A, Fontcuberta J, Molins E, Bellido N, Simon Ch and Fleta C 2006 Nanotechnology 17 687
[11] Ohkoshi S, Kuroki S, Sakurai S, Matsumoto K, Sato K and Sasaki S 2007 Angew. Chem. 46 8392
[12] Dmitriev A I and Morgunov R B 2015 Low Temp. Phys. 41 917
[13] Dmitriev A I, Tokoro H, Ohkoshi S and Morgunov R B 2015 Low Temp. Phys. 41 20
[14] Dmitriev A I, Koplak O V, Namai A, Tokoro H, Ohkoshi S, Morgunov R B 2014 Phys. Solid State 56 1795
[15] Sakurai S, Kuroki S, Tokoro H, Hashimoto K and Ohkoshi S 2007 Adv. Funct. Mater. 17, 2278
[16] Yamada K, Tokoro H, Yoshikiyo M, Yorinaga T, Namai A and Ohkoshi S 2012 J. Appl. Phys. 111 07B506
[17] Du Pre F K 1950 Phys. Rev. 78 615
[18] Van der Ziel A 1950 Physica 16 359