Magnetic properties of NiFeAlO$_4$ nanoparticles

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Introduction
- Magnetic nanoparticles are nanometer-sized particles (<100 nm) of ferromagnetic material
- Magnetic structure is single domain so that nanoparticles can be characterised by their magnetic moment
- We consider the system of many magnetic nanoparticles; the interaction between particles can be neglected
- Magnetic anisotropy tends to direct magnetic moment of the particle along the certain axis
- Two stable orientations of the magnetic moment with the lowest energy are separated by the magnetic anisotropy barrier $U$
- Because of the thermal energy $kT$, magnetic moment of the particle can fluctuate over the barrier
- At high temperatures these fluctuations are quick with respect to the time of measurement
- As the temperature is lowered fluctuations become slower
- Magnetic moment of the particle is blocked on the one side of the barrier for a long time
- Blocking temperature $T_B$ is temperature at which the magnetization of the system relaxes to the equilibrium during the time of measurement
- Relaxation of the magnetization of the system is thermally activated process and relaxation time is given by the Arrhenius law:

$$ \tau = \tau_0 e^{U/kT_B} $$

$\tau_0 = 10^{-2} - 10^{-11}$ s

- In the absence of external magnetic field in the equilibrium state half of the particles are in the left and half in the right well = the total magnetization of the system is zero.
- When the external magnetic field is applied, one will lower its energy and other will increase it = population of the well in the equilibrium will be different resulting in nonvanishing total magnetization of the system

$\tau$ - the system behaves like a paramagnet

- As the temperature is lowered the relaxation time of magnetization becomes longer and at temperatures below the $T_B$, magnetization of the system will not relax to the equilibrium value during the time of the experiment
- These particles, whose magnetic moments at high temperatures fluctuates quickly over the anisotropy barrier, are called superparamagnets: the value of their magnetic moments are much larger than magnetic moments of paramagnetic ions.

NiFeAlO$_4$ nanoparticles
- Spherical-shaped nanoparticles with diameter of 6 nm
- Cubic spinel structure
- Single domain ferrimagnetic structure

Temperature dependence of the magnetization
- ZFC curve: the sample was cooled from the room temperature down to 2 K in zero applied field. Then the magnetic field was applied and magnetization of the sample was measured during the increasing of temperature
- FC curve: the sample was cooled in applied magnetic field and magnetization of the sample was measured during the increasing of the temperature

Magnetic hysteresis loops
- At all temperatures ($\geq 300$ K) hysteresis loops have been obtained
- Magnetic hysteresis is a consequence of the slow relaxation of the magnetization of the system of superparamagnetic nanoparticles
- Applied magnetic field lowers the anisotropy barrier $\propto$ at high temperatures particles have enough thermal energy to overcome the barrier at lower values of the applied field $\propto$ hysteresis loops are narrower at higher temperatures
- Accordingly, the values of the coercive field are lower at higher temperatures
- It is expected that $M(H)$ curve should be reversible above some temperature higher than the room temperature

Relaxation of the magnetization
- The sample was cooled from the room temperature in applied magnetic field to the certain temperature and then magnetic field was reversed
- Magnetization of the sample was measured during ~2.5 h

It is observed that the relaxation of the magnetization is logarithmic
- The logarithmic time-dependence is a consequence of the distribution of the sizes of the particles i.e. distribution of the anisotropy barrier heights

References
1. C.P. Bean, J. D. Livingston, Superparamagnetism, J. Appl. Phys. 30 (1959) 5120-129