Exercise 10 (online: 03.07.2023. Return by: **Mo 10.07.2023 10:00**) **14P**

1. **Magnetic nanoparticles** 10P

   The Stoner-Wohlfarth model describes the angular dependence of the energy E of a spherical, single-domain magnetic nanoparticle with uniaxial crystalline anisotropy by

   $$E = K_1 V \sin^2(\theta) - \mu_0 H M_s V \cos(\theta - \phi).$$

   Here, θ is the angle between the magnetization $\boldsymbol{M}$ and the easy axis, and ϕ is the angle between the external magnetic field $\boldsymbol{H}$ (with $|\boldsymbol{H}| = H$) and the easy axis. Within the entire volume of the nanoparticle one has $|\boldsymbol{M}| = M_\mathrm{s}$ (saturation magnetization). K_1 is the anisotropy constant, and $\mu_0 \approx 1.26 \cdot 10^{-6}\,\mathrm{Vs/(Am)}$ is the permeability of free space. Hint: To shorten your calculations, normalize the energy as $\epsilon = E/(K_1 V)$ and magnetic field as $h = H/H_a$, where $H_a = 2K_1 V/(\mu_0 M_\mathrm{s} V)$ is the anisotropy field.

   (a) **Stability criterion and magnetization reversal.** For the case $\phi = \pi$ and $h \geq 0$ find the stable configurations θ of a magnetic nanoparticle. Show that by increasing h the magnetization reverses at $h = 1$ if the particle was in the state $\theta = 0$ at $h < 1$. (3P)

   (b) **Angle dependence and hysteresis.** Plot the normalized particle energy $\epsilon(\theta)$ for an external magnetic field with an angle to the easy axis $\phi = \pi, (5/6)\pi, (2/3)\pi$ and $\pi/2$ (4 plots in total). In each case use for plotting at least five different magnetic field amplitudes $h = 0, 0.25, 0.5, 0.75$ and 1 (or more). Describe qualitatively the behaviour of the particle magnetization with increasing external field h for the different θ and discuss the connection to the hysteresis loops presented in the manuscript in Fig. 5.18. (4P)

   (c) **Thermally activated magnetization reversal.** Consider a spherical magnetic nanoparticle with $K_1 = 0.2\,\mathrm{J/cm^3}$ and a radius $R = 4\,\mathrm{nm}$ without externally applied magnetic field. How long (on average) should one measure the magnetization of the particle to observe thermally activated magnetization reversal at (i) $T_1 = 300\,\mathrm{K}$, (ii) $T_2 = 77\,\mathrm{K}$? Assume a characteristic time $\tau_0 = 1\,\mathrm{ns}$. The Boltzmann constant is $k_B = 1.38 \cdot 10^{-23}\,\mathrm{J/K}$. (2P)

   (d) **Memory medium**. Assume that a memory medium based on spherical magnetic nanoparticles with $K_1 = 0.2\,\mathrm{J/cm^3}$ and $\tau_0 = 1\,\mathrm{ns}$ should be developed, which guarantees preserving the information for 100 years at room temperature. How large (at least) should be the diameter of the nanoparticles to implement such a memory? Hint: ignore possible effects due to magnetic domains. (1P)

2. **Stoner-Wohlfarth nanoparticle with negative uniaxial anisotropy** 4P

Consider a uniaxial nanomagnetic particle, the energy of which is described by a Stoner-Wohlfarth model

$$E = K_1 V \sin^2\theta - \mu_0 H M_\mathrm{s} V \cos(\theta - \phi) \tag{1}$$

where $H = |\boldsymbol{H}|$ is the magnitude of an external magnetic field, $M_\mathrm{s} = |\boldsymbol{M}|$ is the magnitude of the particle magnetization (constant and homogeneous at all times), and V the particle volume. In contrast to the usual case, the anisotropy constant shall be negative $K_1 < 0$.

Hint: To shorten your calculations, normalize the energy as $\epsilon = E/(|K_1|V)$ and magnetic field as $h = H/H_a$, where $H_a = 2|K_1|V/(\mu_0 M_\mathrm{s} V)$ is the so-called anisotropy field.

(a) **Sketch the system.** Make a simple drawing showing the directions of $\boldsymbol{M}$ and $\boldsymbol{H}$ and explain the two angles θ and ϕ. Consider the case $H = 0$ and plot the normalized energy $\epsilon(\theta)$ for $\theta = -\pi \ldots +\pi$ in a separate graph. What is the meaning of $\theta = 0$, which axis is described by this? (2P)

(b) **Particle groundstate.** We introduce a Cartesian coordinate system with z being the coordinate along $\theta = 0$. In which direction (x, y, z) is the magnetization of the particle pointing for $H = 0$? Could this particle be used for magnetic storage of one bit of information? (2P)