Properties of Nanoengineered Materials Made of Magnetic Particles

D. M. Forrester[1], K. E. Kürten[1, 2], F. V. Kusmartsev[1]

[1]Department of Physics, Loughborough University, Epinal Way, Loughborough, LE11 3TU, UK
[2]Faculty of Physics, University of Vienna, 5, Boltzmanngasse, A-1090, Vienna, Austria

Introduction

The mono-domain magnetic particle is being incorporated into our technologies with breathtaking progress and the characteristics of such particles can be elucidated upon if you pay close attention to the shape anisotropy. The shape anisotropy is a measure of the difference between the energies associated with the magnetisation in the shortest and longest dimensions of the particle. We consider the particles as elliptic cylinders. A long cylinder has a greater magnetostatic energy associated with is magnetisation perpendicular to its major axis than that associated with its magnetisation parallel to the axis. Crudely this can be visualised by considering the closeness of the related but oppositely charged magnetic poles that appear upon the application of an external magnetic field that gives the net magnetisation. Parallel to the axis the poles have a wide separation and low magnetostatic energy. This means that the long axis is the easy axis of shape anisotropy. Axes perpendicular to this axis are hard axes of magnetisation. The energy difference in a cylinder is given in terms of the demagnetising factors. Exact values of these factors can be calculated for uniformly magnetised ellipsoids. Through the axial ratio a/b, where a is the length of the major semi-axis and b the length of the semi-axis perpendicular to it from the centre of the particle we find the demagnetisation factors and the corresponding shape anisotropy energies. K is made dimensionless and its value is zero for a perfectly circular cross section. K increases with the ratio of the semi-axes lengths.

Three magnetic particles

We describe a stack of three single domain ferromagnetic particles separated by insulating layers (see [1-3]) with the aim of shedding light on the complexities of their interaction and their magnetic properties. The energy is described as,

$$\begin{aligned} E &= -J\left(\cos(\varphi_1-\varphi_2)+\cos(\varphi_1-\varphi_3)\right) \\ &-H\left(\cos(\varphi_1-\beta)+\cos(\varphi_2-\beta)+\cos(\varphi_3-\beta)\right) \quad (1) \\ &+K\left(\sin^2\varphi_1+\sin^2\varphi_2+\sin^2\varphi_3\right) \end{aligned}$$

The magnetic field H is applied at an angle β and the magnetisation in the three particles is associated with the three angles $\varphi_{1,2,3}$. The shape anisotropy is defined by the parameter K.

For three magnetic particles the evolution of the magnetic field components in the $x-y$ planes are shown in Fig.1. These are found through the solution of four coupled nonlinear equations: $dE/d\varphi_{1,2,3}=0$ and the Hessian matrix. Each region, separated by a critical line of stability, contains ferromagnetic, antiferromagnetic or canted states in the relationship between the magnetisations in each particle. The critical lines of stability mark the transition in the energy landscape of the minima into saddle points. If each particle has the same magnetisation orientation, we describe the system as having ferromagnetic alignment. Outside the “donut” shape in Fig.1 the particles have this ferromagnetic alignment.

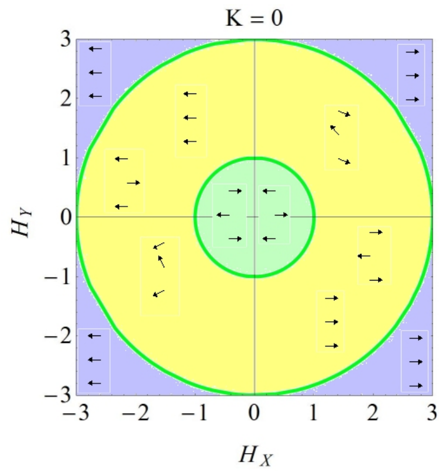

Fig.1 In the H_x-H_y plane the orientation of the stable states in each particle is shown.

Inside the donut there can exist all three possible orientations: canted, antiferromagnetic and ferromagnetic. The “donut hole” is exclusively antiferromagnetic. Each critical line is a perfect circle. Fig.2 shows the magnetisation angle as a function of H in each particle.

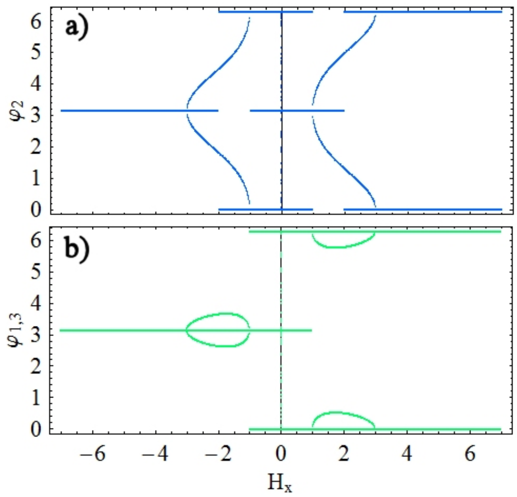

Fig.2 a) Angular evolution in response to the x-component of magnetic field H_x for the central particle b) The outer angles response to H_x

Fig.3 demonstrates how the system characteristics, in terms of the magnetic field components (H_x,H_y), appear for increased levels of anisotropy K. There is clearly an increased complexity here as K increases. Future publications will describe in depth the characteristics of these systems.

Conclusion

The anisotropy is of fundamental importance for practical considerations as it is exploited in the design of many commercially important magnetic materials. Our work should therefore be considered when designing any new technology based materials made of single domain ferromagnetic particles. We expect our results to contribute to the design of new magnetic storage devices and media for tapes or disks. The tapes, made of strongly coupled pairs of such particles, may display many features different from conventional tapes. Synthetic antiferromagnetic nanoparticles, such as in [4], should also emerge as well as the possibility of cellular automata and logic devices. The theories herein should also be applicable to analogous systems such as arrays of Josephson junctions and magnetic tunnel junctions [5].

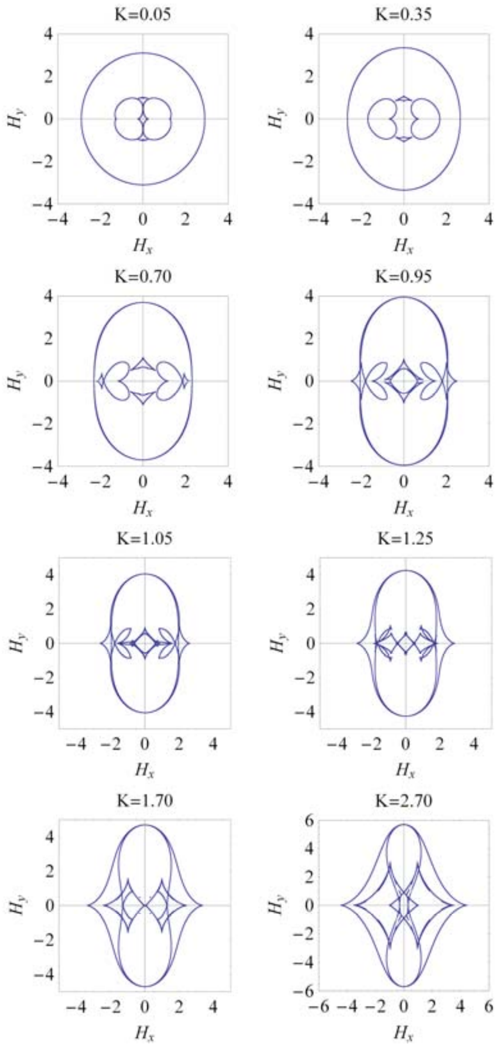

Fig. 3 For anisotropy values varied from K = 0.05 to K = 2.70 the critical lines of stability are shown for the applied magnetic field components H_x and H_y .

References

1. D. M. Forrester, K. E. Kürten, F. V. Kusmartsev, Phys. Rev. B,76,134404 (2007) ; ibid B,75,014416 (2007)
2. D. M. Forrester, K. E. Kürten, F. V. Kusmartsev, E. Kovacs, Journal of Magnetism and Magnetic Materials, Volume 321, Issue 7, Pages 903-905, (2009)
3. D. M. Forrester, K. E. Kürten, F. V. Kusmartsev, E. Kovacs, Int. J. of Mod. Phys. B, Vol. 232, N. 20-21 (2009)
4. W. Hu, R. J. Wilson, A. Koh, A. Fu, A. Z. Faranesh, Advanced Materials, 20, 1479-1483, (2008)
5. D M Forrester, K E Kuerten, F V Kusmartsev, Moldovan Journal of the Physical Sciences, Vol 6, no. 3, 15 pages, (2007)