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SHORT COMMUNICATIONS

Effect of the Shape of an Antiferromagnetic Nanoparticle on Its Magnetization

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Abstract—The dependence of the magnetization of an antiferromagnetic nanoparticle on its shape is studied in terms of a core–shell model. The magnetizations of a nanodisk, nanowire, and spherical particle are shown to differ several fold.

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The study of the properties of antiferromagnetic nanoparticles is of interest for investigating the fundamental problems of surface phenomena and using such materials in practical purposes, namely, superdense recording of information [1, 2] and medicine [3, 4]. Such nanoparticles can form due to biological processes [5, 6] and have a mineral [7] or artificial [1, 7] origin. When an antiferromagnetic sample is small, the sublattices near its surface are uncompensated [8]. It is now generally accepted (see, e.g., [9]) that an antiferromagnetic nanoparticle is considered as an antiferromagnetic core surrounded by a thin shell (core–shell model) whose substance has a spontaneous magnetic moment [10, 11] or weak ferromagnetism induced by surface disordered states with uncompensated spins [12].

The effect of the surface anisotropy [13] and the exchange magnetization of the shell induced by the antiferromagnetic core on the magnetization of an antiferromagnetic nanoparticle placed in a magnetic field are well understood [9]. Nevertheless, we believe that another magnetization formation mechanism should be taken into account in such objects. Depending on the composition and production technique, antiferromagnetic nanoparticles have substantially different shapes. Nanodisks [14] and nanowires [15] were detected apart from near-spherical nanoparticles, and one of the sizes of such irregular nanoparticles differs from the other two sizes by several times or even an order of magnitude. This variety of antiferromagnetic nanoparticles makes it necessary to consider the effect of the shape of a nanoparticle on its magnetization, which can be useful for the investigation of the magnetization reversal mechanisms in magnetic nanoelement arrays in an external magnetic field [16–18].

Using the core–shell model, we consider an antiferromagnetic nanoparticle formed by an ellipsoid antiferromagnetic core with semiaxes a, b, and c and a shell of thickness r with spontaneous magnetization $\mathbf{M}$. The nanoparticle is assumed to be located in external dc magnetic field $\mathbf{H}$ directed along one of the principal exes of the ellipsoid. This field ensures uniform vector $\mathbf{M}$ orientation, determines the magnetization direction, and does not affect the state of the antiferromagnetic core. Then, saturation magnetization $\mathbf{m}$ of the particle is parallel to $\mathbf{H}$ and $m = MV_s/V$, where $M \equiv |\mathbf{M}|$, $m \equiv |\mathbf{m}|$, $V = (4\pi/3)(a + r)(b + r)(c + r)$ is the particle volume, and $V_s = V - (4\pi/3)abc$ is the shell volume (the subtrahend in the right-hand side of this expression means the antiferromagnetic core volume of the particle). Substituting V and V_s into the expression for m, we have

$$m = Mr\frac{ab + ac + bc + r(a + b + c) + r^2}{(a + r)(b + r)(c + r)}. \quad (1)$$

As is seen from this formula, the magnetization of the particle is mainly determined by the ratio of shell thickness r to the characteristic core size and is also dependent on the ratio of semiaxes a, b, and c, i.e., on the particle shape. Equation (1) does not take into account the paramagnetic contribution to the magnetic moment of the sample.

Equality (1) was obtained at an arbitrary ratio of quantities a, b, c, and r, and the effect of the shape of a particle on its magnetization manifests itself as much as possible at a small magnetic shell thickness, $r \ll a$, b, c. In this limit, from Eq. (1) we obtain

$$m \approx Mr\left[\frac{1}{a} + \frac{1}{b} + \frac{1}{c} - r\left(\frac{1}{a^2} + \frac{1}{b^2} + \frac{1}{c^2} + \frac{1}{ab} + \frac{1}{ac} + \frac{1}{bc}\right)\right]. \quad (2)$$

Note that demagnetizing field $H_r \approx 4\pi M$, which hinders magnetization of the sample, appears in it at

small r near the ellipsoid "poles," whose position is determined by the external magnetic field direction. However, the demagnetizing field for nanoparticles is compensated by the exchange field; as a result, external magnetic field $H < H_r$ ($H = |\mathbf{H}|$) is required for the magnetization of this sample.

We now consider several particular cases. Using Eq. (2), for a spherical particle ($a = b = c = R$) we obtain

$$m \approx M\frac{3r}{R}\left(1 - \frac{2r}{R}\right). \quad (3)$$

If an ellipsoid particle is extended along one of its principal axes (nanowire) and the two other principal axes are the same ($a = L_1$, $b = c = R_1$; $L_1 \gg R_1$), its magnetization can be written using Eq. (2),

$$m \approx M\frac{2r}{R_1}\left(1 - \frac{3r}{R_1}\right). \quad (4)$$

Finally, if a particle has the shape of an oblate ellipsoid of revolution, i.e., a nanodisk, ($a = L_2$, $b = c = R_2$; $L_2 \ll R_2$), its magnetization written using Eq. (2) is

$$m \approx M\frac{r}{L_2}\left(1 - \frac{r}{L_2}\right). \quad (5)$$

Note that Eqs. (4) and (5) contain the sizes of the minimum principal axes of an ellipsoid; that is, the magnetization of a nanowire is proportional to the ratio of shell thickness r to antiferromagnetic core radius R_1 and the magnetization of a nanodisk is determined by the ratio of r to antiferromagnetic core half-thickness L_2. If only the demagnetizing and exchange fields are taken into account, the easy magnetization axis of a nanowire is oriented along its length and the easy magnetization axes of a nanodisk are the axes parallel to its plane. The magnetization of the shell of an antiferromagnetic particle is estimated to be $M \propto 10^{-4}$–10^{-3} T. Therefore, the demagnetizing field of the shell is $H_r \propto 10^{-3}$–10^{-2} T, which can coincide with the surface anisotropy field and the exchange magnetization field on the order of magnitude. The low values of the characteristic fields make it possible not to take into account the effect of an external magnetic field on the antiferromagnetic core at $H < H_r$.

It follows from Eqs. (3)–(5) that, at $R \approx R_1 \approx L_2$, the magnetizations of a spherical antiferromagnetic particle and a nanowire are higher than that of a nanodisk by a factor of 3 and 2, respectively. Thus, the dependence of the magnetization of antiferromagnetic nanoparticles on their shape demonstrates that it should be taken into account in investigating such objects and can be useful for practical applications.

REFERENCES

1. S. S. P. Parkin, K. P. Roche, M. G. Samant, P. M. Rice, R. B. Beyers, R. E. Scheuerlein, E. J. O'Sullivan, S. L. Brown, J. Bucchigano, D. W. Abraham, Y. Lu, M. Rooks P. L. Trouilloud, R. A. Wanner, and W. J. Gallagher, J. Appl. Phys. **85**, 5828 (1999).
2. S. E. Russek, J. O. Oti, and Y. K. Kim, J. Magn. Magn. Mater. **198–199**, 6 (1999).
3. P. Tartaj, M. D. Morales, S. Veintemillas-Verdaguer, T. Gonzalez-Carreno, and C. J. Serna, J. Phys. D **36**, R182 (2003).
4. K. G. Dobretsov, V. Yu. Afon'kin, A. K. Kirichenko, V. P. Ladygina, S. V. Stolyar, O. A. Bayukov, and A. V. Sipkin, Bull. Exp. Biol. Med., No. 6, 693 (2009).
5. F. C. Meldrum, V. J. Wade, D. L. Nimmo, B. R. Heywood, and S. Mann, Nature **349**, 684 (1991).
6. S. V. Stolyar, O. A. Bayukov, Yu. L. Gurevich, E. A. Denisova, R. S. Iskhakov, V. P. Ladygina, A. P. Puzyr', P. P. Pustoshilov, and M. A. Bitekhtina, Neorg. Mater. **42** (7), 1 (2006).
7. J. L. Jambor and J. E. Dutrizac, Chem. Rev. **98**, 2549 (1998).
8. L. Neel, Comptes Rendus, **252**, 4075 (1961); **253**, 9 (1961); **253**, 1286 (1961); **254**, 598 (1962).
9. P. K. Manna, S. M. Yusuf, R. Shukla, and A. K. Tyagi, Phys. Rev. B **83**, 184412 (2011).
10. M. A. Morales, R. Skomski, S. Fritz, G. Shelburne, J. E. Shield, M. Yin, S. O'Brien, and D. L. Leslie-Pelecky, Phys. Rev. B **75**, 134423 (2007).
11. V. Markovich, R. Puzniak, D. Mogilyansky, X. D. Wu, K. Suzuki, I. Fita, A. Wisniewski, S. J. Chen, and G. J. Gorodetsky, Phys. Chem. **115**, 1582 (2011).
12. F. N. Sayed, O. D. Jayakumar, C. Sudakar, R. Naik, and A. K. Tyagi, J. Nanosci. Nanotech. **11**, 3363 (2011).
13. J. M. Wesselinowa, J. Magn. Magn. Mater. **322**, 234 (2010).
14. S. N. Klausen, P. A. Lingard, K. Lefmann, F. Bodker, and S. Morup, Phys. Status Solidi A **189**, 1039 (2002).
15. M. J. Benitez, O. Petracic, E. L. Salabas, F. Radu, H. Tuysuz, F. Schuth, and H. Zabel, Phys. Rev. Lett. **101**, 097206 (2008).
16. X. Zhu, P. Grütter, Y. Hao, F. G. Castano, S. Haratani, C. A. Ross, B. Vögeli, and H. I. Smith, J. Appl. Phys. **93**, 1132 (2003).
17. Yu. L. Raikher and V. I. Stepanov, JETP **107**, 435 (2008).
18. V. L. Mironov, A. A. Fraerman, B. A. Gribkov, O. L. Ermolaeva, S. A. Gusev, and S. N. Vdovichev, Phys. Solid State **52**, 2297 (2010).

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