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ALTERATIONS IN NANOMAGNET ENTRANCES INDUCED BY FIELD AND TEMPERATURE

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ABSTRACT: The paper investigates how magnetic entropy varies in nanostructures used for magnetic cooling when the temperature remains constant using model computations. The magnetic entropy is calculated using the mean-field approach, which takes temperature, magnetic field, particle size, anisotropy, and contact strength into account. We consider both isotropic (Heisenberg) and uniaxial anisotropies (Ising and XY). The anisotropy of nanoparticles has a significant impact on their entropy. The energy of anisotropy in atomic ferromagnetism, on the other hand, is substantially smaller than the energy of contact. Isotropic particles, easy-plane particles having a field in the plane, and particles with mild easy axis anisotropy are some of the particles that show the most promise. Nanoparticles should not be larger than 1 nm in size since their relative magnetic direction changes little and has little effect on the entropy change.The researchers utilized model calculations to investigate how magnetic entropy varies in nanostructures used for magnetic cooling when the temperature remains constant. The magnetic entropy is calculated using the mean-field approach, which takes temperature, magnetic field, particle size, anisotropy, and interaction power into account. We consider both isotropic (Heisenberg) and uniaxial anisotropies (Ising and XY). The anisotropy of nanoparticles has a significant impact on their entropy. In contrast, in atomic ferromagnetism, the energy from anisotropy is substantially lower than the energy from interactions. The most promising particles include isotropic particles, easy-plane particles with a magnetic field that stays in the plane, and particles with mild easy axis anisotropy. Nanoparticles should not be larger than 1 nm in size since their relative magnetic direction changes little and has little effect on the entropy change.

Key words: Nanomagnets,Temperature-induced entropy changes,Magnetic materials

Magnetic cooling is an energy-saving and environmentally friendly technology. To begin with, magnetic refrigerators are better for the environment since they do not contain chemicals that deplete the ozone layer. Furthermore, cooling is more efficient than gas compression refrigeration. Scientists are currently conducting extensive research on magnetic refrigeration at room temperature. However, the concept of adiabatic demagnetization of paramagnetic materials has long been used in low temperature physics.The range is from 1 to 3. Many contemporary kinds of magnetic cooling rely on atomic characteristics, particularly the spin orientation of Gd 4f shells in magnetic compounds. The primary focus of both basic and applied research has been on bulk materials that are easy to produce in large quantities, such as Gd3Ge2Si2,1,2. Nonetheless, there aren't many compounds that are safe to use. Almost all chemicals exhibit the magnetocaloric effect. The rise in entropy, on the other hand, is normally minimal and only becomes noticeable when the temperature and field are not optimal. Nanostructures open up new avenues for improving material properties, such as employing magnetocaloric effects.3-5: A magnetic field of 10 kOe or less can modify the magnetization of certain nanostructures, for example. It is not necessary to employ superconducting magnets because this may be accomplished with solid magnets such as Nd2Fe14B.Six and seven are present.

Magnetic refrigeration makes use of the entropy shifts that occur in spin systems. It all starts with pure energy.

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$$F = U - TS - \mu_0 \int \mathbf{M} \cdot \mathbf{H} dV, \qquad (1)$$

U denotes internal energy, T the temperature, M the magnetization, and H the magnetic field. The entropy employed in magnetic cooling is determined by how atoms' magnetic moments align with one another. A magnetic field can modify both the entropy (S) and the temperature (TS). Even though a magnetic field causes spins to line up, lowering entropy, the Zeeman energy (0) M • H dV is only partially taken into account in the magnetic entropy balance. Consider nanoparticles composed of N Sat atoms with a spin of 1-2 or N spins with a moment of B (spin 1-2), where Sat is the number of spins per atom (Sat=7-2) in Gd3+. Both the Curie transition (a) and a Stoner-Wohlfarth-type micromagnetic magnetization rotation (b) are prevalent in small particles and are depicted in Figure 1 next to each other. It's also worth noting that variations in the magnetization of nanostructures frequently exhibit micromagnetic properties that have nothing to do with entropy or temperature effects (see Figure 2). The magnetic entropy of exchange-coupled and non-interacting nanoparticles is investigated in this paper, with an emphasis on how particle size and anisotropy affect it.

The partition function is used to determine the best entropy.

$$Z = \Sigma_i \exp(-E_i / k_B T),$$

where the aggregate takes into consideration all the states that are actually reached in a normal experiment or application cycle. Magnetic nanostructures, on the other hand, frequently constrain the directions of relative magnetism, despite the fact that thermodynamic stability is typically limited to length scales of 1 nm or less. Ergodicity is required for equilibrium thermodynamics to work.There are seven and eight of them. There is a difference in how mechanical glasses act when they are liquid-like snapshots of glass components and when they are solid-like fixed atomic configurations. As a result, they are nonergodic.

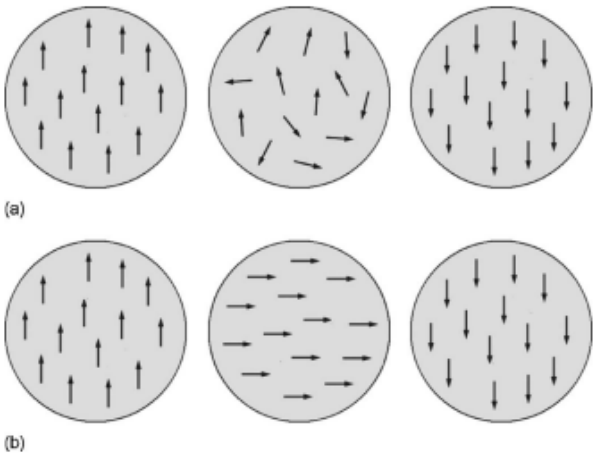

FIG. 1. Magnetic fields including nanoparticles can suffer phase shifts and magnetization reversals. The majority of changes fall into category (b), which means that entropy has no effect on the particle's relative spin orientation. Each atomic spin is represented by an arrow.

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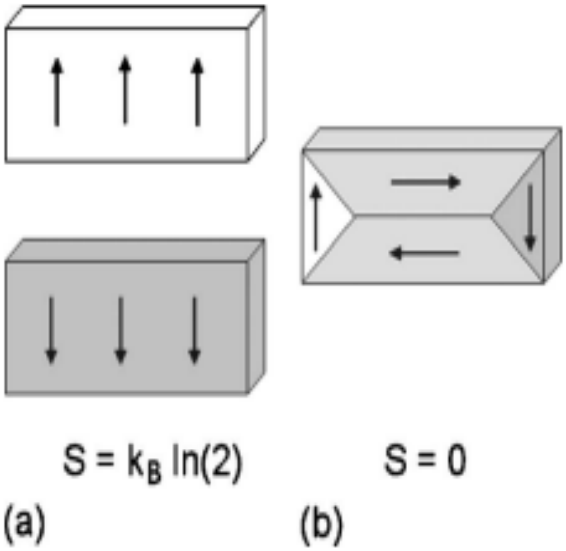

FIG. 2. Thermal dynamics fluctuations and the micromagnetic regime both achieve zero net magnetization.

Thermal averages are obtained from the well-known relation $\langle A\rangle=\Sigma_i p_i A_i$, where $p_i=\exp(-E_i/k_BT)/Z$ is the probability of encountering the ith state. This includes the expression $S=-k_B\Sigma_i p_i \ln(p_i)$ for the entropy. Free isotropic particles, as well as isotropic particles interacting in the mean-field approximation, obey $E_i=-\mu_0\mu_B H s_{zi}$, so that S becomes a function of the magnetization. Furthermore, the entropy of nanoparticles exhibits a pronounced dependence on the magnetic anisotropy. This is in contrast to atomic ferromagnetism, where the anisotropy (less than 1 K per atom) is much smaller than the exchange (more than 100 K per atom) and important only in the vicinity of T_C. Nanoparticle anisotropy energies roughly scale as $N\sim R^3$ and are often larger than the interparticle interaction.

In the following, we will describe our magnet by the quasiclassical mean-field Hamiltonian,

$$\mathsf{H}=-NJ_{\rm eff}m\langle m\rangle-NK_u m^2-N\mu_0\mu_B Hm, \qquad (2)$$

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where K_u is the uniaxial anisotropy per spin,[6,8] m is a dimensionless and normalized magnetization variable, and the exchange J_{eff} describes the interaction between the particles. Dipolar interactions require more elaborate mean-field Hamiltonians, because they may lead to the formation of columnar structures, but otherwise they affect the entropy in a manner similar to exchange.

Let us first neglect the interaction and compare isotropic magnets with uniaxial magnets of anisotropy constant K_u (both easy axis and easy plane). There are two well-known and rather trivial high-temperature limits, namely, isotropic particles ($K_u=0$) and Ising magnets ($K_u=\infty$). Isotropic particles have $2N+1$ Zeeman-split states and $S=k_B \ln(2N+1)$, or $S=k_B \ln(2N)$ in the approximation of Eq. (2), whereas Ising magnetism corresponds to two states $\uparrow$ and $\downarrow$ with equal probability and $S=k_B \ln(2)$. For arbitrary fields and temperatures, the free energy

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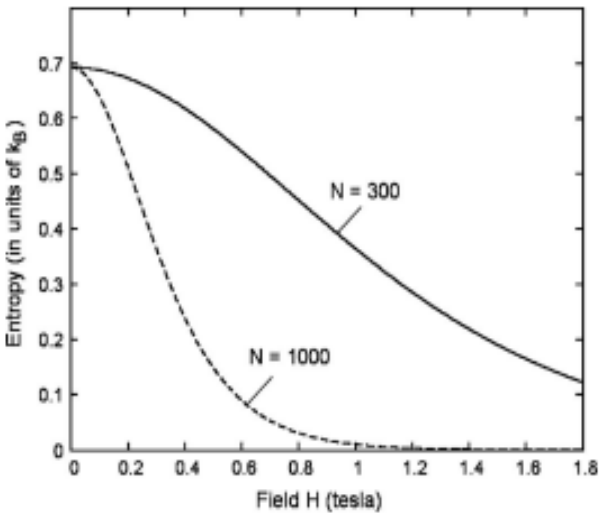

FIG. 3. Entropy of Ising spin clusters.

$$F = -k_B T \ln\left(2\cosh\frac{\mu_B N H}{k_B T}\right) \tag{3}$$

of an Ising spin yields the well-known equation of state $M = \mu_B \tanh(\mu_B N H / k_B T)$ and the entropy

$$S = k_B \ln\left(2\cosh\frac{\mu_B N H}{k_B T}\right) - \frac{\mu_B N H}{T}\tanh\frac{\mu_B N H}{k_B T}. \tag{4}$$

This entropy decreases from $S = k_B \ln 2 - \mu_B^2 N^2 H^2 / 2 k_B T^2$ in small fields to $S = 0$ in large fields. Fig. 3 shows the room-temperature entropy for two particle sizes.

The calculation of the partition function for intermediate anisotropy[8] requires some bookkeeping but is straightforward. Figure 4 shows the room-temperature entropy of non-interacting particles as a function of the anisotropy field $H_a = 2K_u V_{at} / \mu_0 \mu_B$, where V_{at} is the volume per spin. Fields between 0 and about 1 T are easily created by permanent magnets, and the corresponding entropy gain corresponds to gray area in Fig. 2. We see that isotropic magnets ($H_a = 0$) and

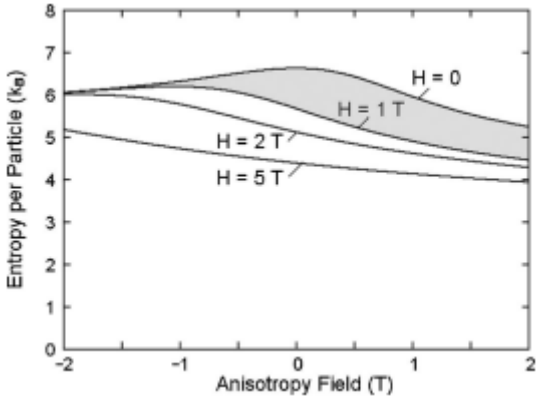

FIG. 4. Nanoparticles have 1000 atomic spins, and their entropy at ambient temperature relies on their field. Isotropic magnetism, easy-plane anisotropy, and easy-axis magnetism are connected to anisotropy fields with negative, zero, and positive values in that order. This "gray area" refers to the range of field strengths that permanent magnet devices are capable of producing.

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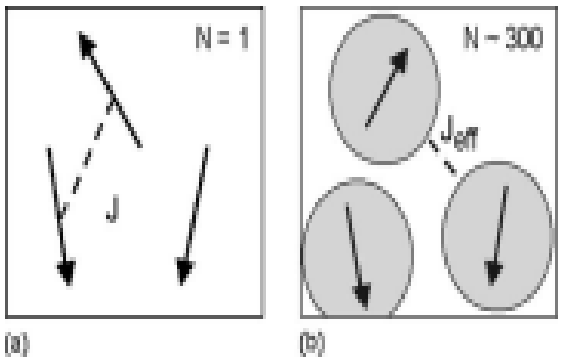

FIG. 5. Atomic spins interact with nanoparticles in solid-state materials, affecting entropy. This results in molecular melting.

Large entropy shifts are caused by magnets with moderate easy-axis anisotropy (Ha > 0). Because the entropy resulting from easy-plane anisotropy (Ha 0) is mostly limited to the basal plane, the field component aligned with the line has little effect. We can demonstrate that in-plane fields cause a large amount of entropy.

Connections (Jeff) in atomically structured magnets can raise entropy differences (Figure 5). Equation (4) employs the Jeff term in H to calculate mean-field entropy. Figure 6 compares the entropies of particles that interact vs those that do not interact. When contact strength Jeff kB approaches room temperature, the solid line in Figure 6 is quite effective. The system operates like large bulk magnets with significant couplings, but there is no apparent effect with minor interactions. Even if the maximum entropy density change is large, the connection does not require fine-tuning. The entropy of nanoparticles changes in small areas.

$(J_{eff}=k_BT)$ is $\frac{5}{4}(\mu_0\mu_BH/k_BT)^{4/3}N^{1/3}$,

as compared to the term

$\frac{1}{2}(\mu_0\mu_BH/k_BT)^2N$

briefly discussed below $1/2$ is $\ln(2N)$, The maximum entropy of a particle containing N atoms of spin 1/2 is ln $(2N)/N.$ so that the entropy per atom is ln. This entropy scales as 1/N, and there is no point

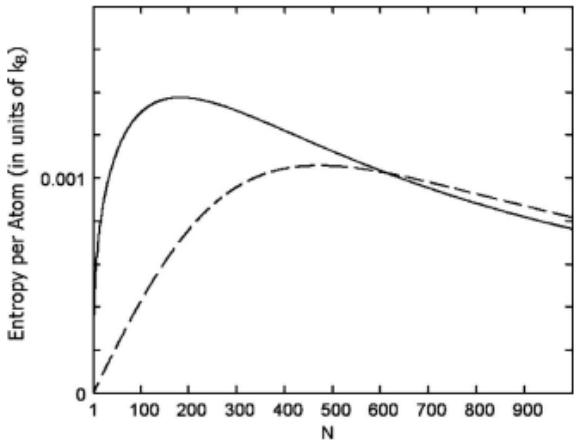

FIG. 6. The straight lines represent particles interacting in a 1 T magnetic field, whereas the dashed lines represent particles that are not interacting. The mean-field approach is intended to produce better results when the temperature is near to room temperature.

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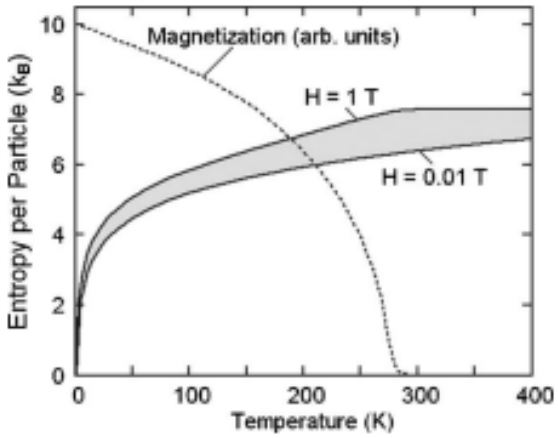

FIG. 7. Nanoparticles have 1000 spins, 1150 K net interparticle exchange, and a 0.1 T anisotropy field. The entropy of these particles varies as the temperature rises. Magnetic cooling is delivered to the dark area using very big particles. Entropy correlations produced by different spin models are comparable. A few hundred spins at ambient temperature are sufficient to generate magnetic fields of around 1 Tesla, given that = 0.672 K T (see Figure 7). Contacts can be used to obtain smaller magnitudes. We support the deployment of a hybrid system that functions at a level halfway between atomic and nanoscale cooling and takes advantage of the best aspects of each. In the actual world, examples include embedded nanoparticles that form weak connections via RKKY-type exchange (10,11) and multilayered magnets with opposing ferroelectric and antiferromagnetic interactions.The number is twelve.

Finally, the magnetic cooling properties and entropy increase of nanostructures have been investigated. Because the magnetization directions within the nanoparticles remain constant, the entropy change per atom is marginally lower. As a result, when the temperature and magnetic field are low, nanostructuring increases the entropy change. Magnetic anisotropy, which has a large effect on magnetic entropy, is a significant feature of magnetic nanoparticles. This could be useful for magnetic cooling.

CONCLUSION

In conclusion, the study of temperature- and field-induced entropy changes in nanomagnets represents a fundamental exploration into the thermodynamic behavior of magnetic systems at the nanoscale. The observation and understanding of how these systems respond to changes in temperature and magnetic field offer valuable insights into the dynamics of magnetization, laying the groundwork for potential applications in various technological domains.

The reversible and tunable entropy changes observed in nanomagnets under external stimuli hold promise for magnetic refrigeration, energy-efficient cooling systems, and sensor technologies. These findings underscore the potential of nanomagnetic materials to revolutionize thermal management processes by providing a pathway towards more efficient and environmentally friendly cooling technologies.

However, challenges such as achieving optimal operating conditions, improving material properties, and enhancing the scalability of these nanomagnetic systems need to be addressed to realize their full potential in practical applications. Additionally, further research is essential to comprehensively understand the underlying mechanisms governing entropy changes in nanomagnets and to develop advanced modeling techniques that can predict and optimize these effects.

Collaborative efforts across interdisciplinary fields, including physics, materials science, and engineering, will be pivotal in overcoming these challenges and harnessing the potential of temperature- and field-induced entropy changes in nanomagnets. With continued exploration and innovation, these discoveries could pave the way for transformative advancements in energy-efficient cooling technologies and novel sensor applications.

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