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ABSTRACT
We report a theoretical investigation of new magnetic phases of thin terbium (Tb) films in the temperature interval between 220 K and 280 K, and under external magnetic field strengths ranging from 50 Oe to 1 kOe. We show that surface effects may produce relevant changes in the helimagnetic phase, such as the nucleation of alternating-helix phases. Changes in the exchange energy balance near the surface, favor the alignment with the external field and the nucleation of the alternating-helix phase.

I. INTRODUCTION
Considerable research effort has recently been dedicated to investigating the impact of confinement as well as surface effects on the equilibrium phases of magnetic systems with size comparable to fundamental magnetic lengths.

These confinement and surface effects are particularly interesting in magnetic systems in which the leading bulk magnetic phases consist of patterns made of a periodic repetition of units containing a finite number of spins. This is the case of the helical structure of rare earth metals, and the helix period is a valuable length scale to predict the impact of finite size effects.

Several surface-induced features, as well as confinement effects of thin helimagnetic films, have recently been discussed. For instance, it has been shown that there is a strong thickness dependence of the Neel temperature of Ho thin films, indicating that the helical state does not form in Ho films with thickness below a threshold value corresponding to ten atomic layers. Furthermore, it has been theoretically shown that wide thermal hysteresis loops may be induced in Dy thin films subjected to external magnetic fields of modest strength. The thermal hysteresis of thin Dy films is induced by an alternating-helix phase associated to the locking of surface spins to the external field direction.

The alternating-helix phase may nucleate either in thin helimagnetic films or in multilayers. The alternating-helix phase comprises helix with opposite chirality within the film, leading to an increase in the total magnetic moment in the direction of the external field compared to the simple helical state.

Terbium has a rather narrow helimagnetic phase, from 220 K to 230 K. The basal plane hexagonal anisotropy is rather small at this temperature range. Thus, the helimagnetic phase is isotropic. Furthermore, in thin films the near surface region has a relevant change in the balance of first and second neighbors exchange energies. These two features allows the manipulation of the helimagnetic order of thin Tb with relatively modest external field values.

In this paper, we present a theoretical discussion of the nucleation of alternating-helix phases in thin terbium films. These phases are associated to the confinement of surface atoms magnetic moments directions to directions near the external field direction. We consider external fields oriented along the b-axis directions in the basal plane, as shown in Fig. 1.

II. THEORETICAL MODEL
We investigate a c-axis Tb thin film, consisting of a stacking of atomic layers with equivalent spins, infinitely extended in the x-y directions. The spins in each monolayer are exchange coupled with the spins in the first and second neighbor monolayers. We investigate the magnetic phases in temperature intervals near the Neel temperature. The Hamiltonian corresponding to the magnetic energy
The self-consistent local field algorithm allows taking into account the impact of the modifications of the exchange interactions, due to the reduced coordination near the surfaces, the overall relaxation of surface effects towards the middle of the thin film, the change in the strength of the effective exchange fields with the temperature, and the effect of the external magnetic field.

The effective local field $H_{\text{eff}}^n$ at the n-th plane is obtained from the gradient of the magnetic Hamiltonian $\mathcal{H}$: $H_{\text{eff}}^n = \frac{1}{\partial \mathcal{H}} \frac{\partial \mathcal{H}}{\partial \phi_n}$. The thermal average values of the total angular momentum at each plane are calculated using a Brillouin function average for each atom, $<J_n> = \sum\phi_n (\frac{g\mu_B J_n}{k_B T})^6$, where $J$ is the quantum number used for the total angular momentum, and $g\mu_B$ is the saturation value of the Tb-atom magnetic moment at the n-th plane.

In thin helimagnetic films, the spins in different atomic layers are not equivalent. Considering a Hamiltonian $\mathcal{H}$ with the exchange energy restricted to second neighbor spins, only the spins in the two planes near the surfaces are directly affected by the reduction of the coordination number, and exchange energy, near the surfaces. However, surface effects are not restricted to these near surfaces atomic planes. The number of planes affected by surface effects depend on the relaxation of the effective local field from the near surface to the bulk pattern in the middle of the film. The relaxation pattern is very likely to be temperature dependent.

Owing to the relaxation of surface effects from the surface planes to the middle of the film, describing the nature of the magnetic phases of helimagnetic materials thin films poses the theoretical challenge of predicting, at the same time, the spatial orientation of the thin film spins, as well as the spin thermal average values, which requires predicting the effective exchange fields of nearest neighbor spins.

The confinement of helimagnetic materials in thin films may lead to relevant changes in the intrinsic magnetic phases.

From the modeling point of view, one needs a theoretical frame that allows representing the spatial variations of the effective non-local magnetic parameters, such as the exchange energy, and simultaneously incorporates the thermal effects in a simple and effective manner. This is the basic strategy of the theoretical model we use presently, which was also applied to other subjects in the past.

Motivated by the experimental report of the suppression of the helix in Ho thin films, for film thickness below ten atomic planes, we have investigated theoretically the impact of confinement in Dy thin films. In this former we have found that owing to the suppression of the helix, thin Dy films may exhibit giant magnetocaloric effect.

Similar theoretical modelling was used successfully in the past to investigate superlattice effects found in rare-earth multilayers. New magnetic states were reported from the interpretation of field cooling experiments in Dy/Gd superlattices. The new magnetic states were found to emerge from the intrinsic properties of the components and the interaction between Dy and Gd layers.

III. RESULTS

In Fig. 1 we show a schematic representation of the magnetic phases of the 18 layers Tb film for a temperature of 220 K and external field strengths of (a) 300 Oe and (b) 500 Oe. The figures show the directions, in the basal plane, of the magnetic moments of each layer. The confinement of helimagnetic materials in thin films poses the theoretical challenge of predicting, at the same time, the spatial orientation of the thin film spins, as well as the spin thermal average values, which requires predicting the effective exchange fields of nearest neighbor spins.

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There is a bunching of spins near the external field direction ($\varphi_{H} = 30^\circ$). In Fig. 1(a) for external field strength of 300 Oe, the total angular span is $\Delta\varphi = 80^\circ$, corresponding to magnetic moment orientations in the basal plane in the interval $\varphi_{H} \pm 40^\circ$, with the $n = 18$ surface layer magnetic moment aligned with the external field. Starting from the $n = 1$ surface layer up to the $n = 4$ layer the magnetic moments turn by small angles in the counter-clockwise sense. From the $n = 5$ layer up to the $n = 13$ layer the magnetic moments turn in the clockwise sense, and from the $n = 14$ up to $n = 18$ layer the magnetic moments turn in the counter-clockwise sense.

In Fig. 1(b) for external field strength of 500 Oe, the total angular span is smaller ($\Delta\varphi = 54^\circ$), corresponding to magnetic moment orientations in the interval $\varphi_{H} \pm 27^\circ$. In this case the total angular span is narrower because the external field strength is larger. The chirality alternation through the film follows the same pattern as in Fig. 1(a).

The bunching of magnetic moments around the external field direction results in part from the fact that near the surfaces, because of the reduction of the coordination number, the ferromagnetic coupling between nearest neighbor planes is favored. Also, in the temperature range from 200 K to 280 K the Tb film is isotropic ($K_{B} \approx 0$), and the field direction is favored.

In Fig. 2, we show isofield magnetization curves for an 18 atomic layers Tb film in the temperature range from 220 K to 280 K. All magnetization curves display a monotonic decrease with temperature, because the external magnetic field strengths considered are moderately large (from 300 Oe to 1 kOe). In the inset we show the alternating-helix at 220 K for an external field strength of 500 Oe, as discussed above in connection with the data in Fig. 1.

In Fig. 3, we show isofield magnetization curves for an 18 atomic layers Tb film in the temperature range from 220 to 240 K and external field strengths from 50 Oe to 800 Oe.

In the insets, in Fig. 3, we show the schematic pictures corresponding to the magnetic patterns of alternating-helix phases that form at the isofield curve for $H = 100$ Oe, at a temperature of 225 K, and for $H = 200$ Oe at a temperature of 225 K. The pictures are similar and the total angular span values are $105^\circ$ and $88^\circ$, respectively. The smaller angular span of $88^\circ$ is due to the larger external field strength.

Interestingly, the features shown above in the isofield magnetization curves of Tb thin films, have also been reported from magnetization measurements in Tb crystals.\textsuperscript{[1]}

In addition, apart from the effect on the thin Tb film net magnetic moment, there are also new effects in the magnetic phases near the Neel temperature. In this temperature range, even for moderate values of the external field strength, one may induce interesting changes in the Tb magnetic phases.

Notice that the magnetization curves for moderately large external field strength values (500 Oe and 800 Oe) show a monotonic decrease with the temperature, while for small values of the external field strength, from 50 Oe to 200 Oe, there is an abrupt drop of the magnetization, near the Neel temperature, followed by a peak just after the Neel point.

We have found that the magnetization drop at the Neel point corresponds to an abrupt increase in the alternating-helix total angular span (to $\Delta\varphi \approx 120^\circ$, corresponding to magnetic moments orientation with the external field in the interval $\varphi_{H} \pm 60^\circ$), while the maxima observed in the isofield magnetization curves, just after the Neel point, correspond to the nucleation of a ferromagnetic order, in the place of the alternating-helix phase, with an increase in the net magnetic moment per atom along the external field direction. Further increasing the temperature leads to dropping the thermal average angular momentum per atom, as well as the net magnetic moment.

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Interestingly, the features shown above in the isofield magnetization curves of Tb thin films, have also been reported from magnetization measurements in Tb crystals.\textsuperscript{[1]}
If the external field strength is of the order of the intrinsic exchange fields, it may produce new arrangements of spins. Owing to the prevalence of ferromagnetic coupling in the near surface region, due to the lack of second neighbor antiferromagnetic exchange coupling, one may find a bunching of spins in the near external field direction. This bunching of spins near the easy axis direction competes with the trends imposed by the first and second neighbors exchange energy, which require the helical structure, and may lead to modifications in the helical phase, such as an alternate chirality helix.

IV. CONCLUSIONS

We have discussed the isofield magnetization curves for a Tb thin film and found that near the Neel point, even with modest values of the external field strength, ranging from 50 Oe to 200 Oe, one may find interesting features in the magnetization curves. Furthermore, we have shown that if the external field strength is of the order of the intrinsic exchange fields, it may produce new arrangements of spins. Owing to the prevalence of ferromagnetic coupling in the near surface region, due to the lack of second neighbor antiferromagnetic exchange coupling, one may find a bunching of spins in the near external field direction. This bunching of spins near the easy axis direction competes with the trends imposed by the first and second neighbors exchange energy, which require the helical structure, and may lead to modifications in the helical phase, such as an alternating helix.

The alternating-helix phase consists of helical segments with alternating chirality leading to an enhancement of the net magnetic moment along the external field direction.

We have shown that the total angular span of the alternating-helix phase around the external field direction may be tailored by choosing the field strength and the temperature.

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