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# The magnetic structures of holmium–yttrium superlattices in an applied magnetic field

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**Abstract.** The magnetic structures of a rare earth superlattice in an applied magnetic field have been determined using neutron scattering techniques. The sample was grown using the LaMBE facility in Oxford and the periodic unit consisted of 41 planes of holmium and 16 planes of yttrium. The results showed four different types of magnetic phase corresponding to the helix, helifan, fan and ferromagnetic phases observed when a magnetic field is applied in the basal plane of bulk holmium. In the superlattice the correlation length was very long for the ferromagnetic phase, about 10 superlattice periods for the helix, about 4 superlattice periods for the fan and there was little, if any, correlation between the superlattice blocks for the helifan phase. The structures depended in detail upon the history in field and temperature as the configuration was approached. The most striking aspect of the result is that the helical phase is stable to higher fields in the superlattice than in the bulk. It is argued that this is because the conduction electron susceptibility in yttrium favours a modulated structure more strongly than in holmium and that the propagation of conduction electrons throughout the superlattice transfers this enhancement to the holmium blocks.

## 1. Introduction

The magnetic structures of the rare-earth metals result from the competition between the exchange and the crystal field interactions. The former are moderated by the conduction electrons and tend to favour magnetic structures which are incommensurate with the underlying crystal structure, while the latter arise from the local environment and the properties of the 4f electrons and tend to favour particular directions for the magnetic moments [1]. When a magnetic field is applied there is a third interaction and the magnetic structures are more complicated [2]. In the absence of an applied magnetic field, holmium metal orders magnetically below 132 K and the structure is a basal plane helix while below 18 K it is a cone. When a magnetic field is applied in the basal plane other magnetic structures are observed [3, 4] including a basal plane ferromagnetic phase, a fan phase and a helifan phase.

For the past 15 years it has been possible with molecular beam epitaxy (MBE) to grow superlattices consisting of layers of the rare-earth metals separated by layers of non-magnetic metals such as yttrium and lutetium. The magnetic structures of the holmium layers are similar to those of the bulk rare earth metals and are coherent through the non-magnetic layers of the superlattice (SL) [5, 6]. In this paper we report on the magnetic structures which occur when

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a magnetic field is applied to a SL. We have chosen to study a holmium/yttrium SL because the phase diagram of bulk holmium in a magnetic field shows a richer variety of magnetic phases than other heavy rare-earth metals and we wished to study whether this richness also arose for the superlattices. The particular sample chosen was $[Ho_{41}/Y_{16}]_{50}$ for which analysis of x-ray scattering data showed [6] that there are 41 atomic planes in each holmium layer and 16 planes in each yttrium layer and this bilayer unit is repeated 50 times. The magnetic structures were studied by neutron scattering techniques in the absence of a field by Jehan *et al* [6] and the ordered magnetic structure is a coherent basal plane helix. We have used neutron scattering techniques to determine the phase diagram and structure of the magnetic phases when a magnetic field is applied in the basal plane of the SL. Section 2 describes the growth and structural properties of the SL and gives details of the neutron scattering experiments. The third section describes the analysis of the experimental results to determine the type of magnetic structure. These magnetic structures and the resulting phase diagram are described in the fourth section and are discussed in a final section together with a comparison with the results of magnetization measurements on Ho/Y superlattices in a magnetic field [7, 8].

## 2. The superlattices and the neutron scattering measurements

The Ho/Y SL was grown by MBE techniques using a Balzers UMS 630 facility. A Nb chemical buffer was deposited on a sapphire substrate to chemically isolate the substrate from the rare-earth metals. A Y seed layer was grown on the Nb layer with a thickness of about 1000 Å and the SL was grown at a temperature of 570 K at a rate of 0.5 Å $s^{-1}$. A 300 Å Y capping layer was grown on top of the SL to prevent reaction of the SL with the atmosphere. The crystallographic orientation is controlled by the epitaxy of the $Al_2O_3$/Nb/RE system.

The crystal structure of the SL was determined using a triple-axis x-ray diffractometer mounted on a Stoe rotating anode generator operating at 6 kW. The x-ray measurements confirmed that the Ho/Y SL was grown with the hexagonal $(00l)$ atomic planes perpendicular to the growth direction and the structure was $[Ho_{41}Y_{16}]_{50}$, while the mosaic spread was $0.19^\circ$, the structural correlation length of the SL 1800 Å and the interface width about 3.5 atomic planes [9]. The neutron scattering measurements were performed at the DR3 reactor of the Risø National Laboratory in Denmark. The SL was mounted within a vertical field superconducting magnet so that the [001] and [100] reciprocal lattice vectors of the hexagonal rare-earth structure were in the horizontal scattering plane and perpendicular to the magnetic field. The cryomagnet was placed on the TAS6 triple axis spectrometer and the applied magnetic field could be varied between 0 and 6 T with an accuracy of 0.01 T and the temperature of the SL varied between 5 and 300 K with a precision of 0.05 K. The spectrometer was used with a pyrolytic graphite monochromator and analyser so as to measure the elastically scattered neutrons when the incident neutrons had a wavelength of 2.351 Å. A pyrolytic graphite filter was used to suppress the higher energy contaminant neutrons reflected by the monochromator and the collimation was chosen so that the wave-vector resolution in the scattering plane was typically 0.071 $Å^{-1}$ (FWHM).

The scattered intensity was obtained by scanning the wave-vector transfer along the $[00L]$ direction and recording the intensity of the scattered neutrons. Most of the measurements were made by cooling the sample to about 5 K in a fixed magnetic field then measuring the intensity at successively higher temperatures while keeping the magnetic field constant. This procedure was used for magnetic fields of 0, 1, 2, 3, 4 and 5 T. Some scans were performed with the field fixed at 3 T while the sample progressively cooled from a temperature of 80 K. Finally the temperature was held fixed at 80 K while the magnetic field was varied between 6 and 0 T.

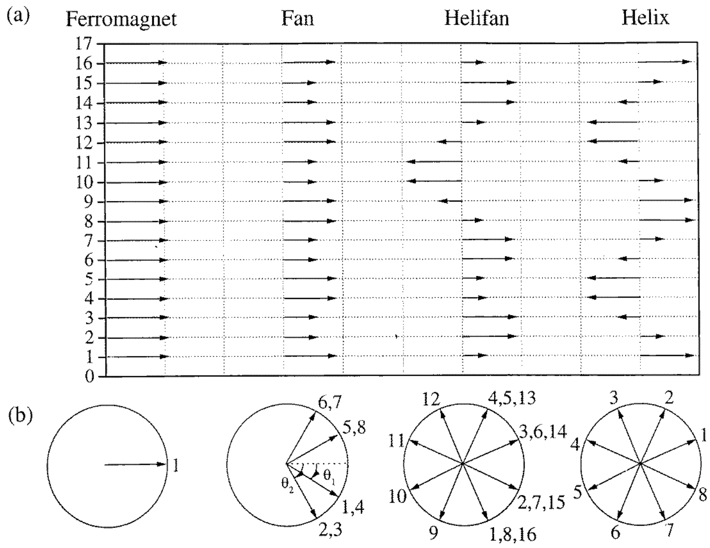


**Figure 1.** (a) Projections of the moments along the applied field direction and (b) in the perpendicular basal plane direction for the moments of a ferromagnet, fan, helifan and helix assuming in each case that four successive planes are all aligned parallel or anti-parallel to the applied field direction.

## 3. The neutron scattering cross-section

The neutron scattering from an ideal SL is a product of the scattering from a single repeating unit (block) of the SL and the reciprocal lattice of the SL. Initially therefore we shall consider the scattering from a single magnetic block. Experiments on bulk holmium in a basal plane magnetic field have shown that the magnetic structures have the moments of the holmium atoms in each basal plane aligned ferromagnetically but that the direction of the moments of different basal planes alters. Five different arrangements of the magnetically ordered planes occur: a basal-plane helix, a basal-plane fan structure, a helifan, a basal-plane ferromagnet and a cone structure [4]. The cone phase does not occur in the SL [6] and so we consider the scattering from the other four phases. In figure 1 are shown illustrations of these four structures where, for simplicity, the periodicity was assumed to be such that the structures have four successive planes with the components of their moments either parallel or anti-parallel to the magnetic field. The helix has alternate groups parallel and anti-parallel, the helifan has 2/3 of the groups parallel and 1/3 anti-parallel, the fan all groups parallel and the ferromagnet is a special case of the fan in which the opening angle of the fan, $\theta = 0$.

The scattering from 40 atomic planes having these different structures, or equivalently the structure factors for the Bragg reflections of an SL with these four different repeating units, is shown in figure 2 for the case when the wave-vector transfer, $\boldsymbol{Q}$, is along the $[00L]$ direction. In the case of the helix the scattering occurs largely near $L = 1.75$ and 2.25, where $L = 2 - q$ is in units of the hexagonal $c$-axis reciprocal lattice vector ($c^* = 2\pi/c$). It has a width that corresponds to that expected for the scattering from a single block of 40 holmium planes. The scattering from a ferromagnetic block is similar in shape but centred at the bulk Bragg reflection $L = 2.0$. The scattering from the fan phase has two components. The components along the magnetic field are ferromagnetically aligned and the scattering from

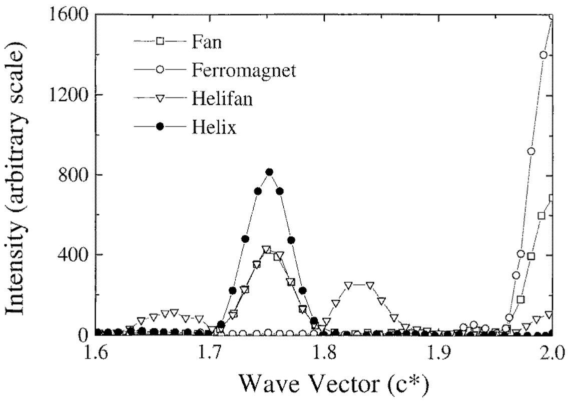


**Figure 2.** The magnetic scattering or SL form factor for 40 planes of holmium. The magnetic structures are a ferromagnetic phase, a fan phase with $\theta_1 = \pi/8$ and $\theta_2 = 3\pi/8$, a helifan phase with the angle between successive planes $\theta = \pi/4$ and a helix with an angle of $\pi/4$ between successive planes.

them is centred near $L = 2.0$. The variation in the length of these ferromagnetic components gives weak scattering near $L = 1.5$ and 2.5. The components of the moments perpendicular to the magnetic field oscillate and give rise to scattering near $L = 1.75$ and 2.25, but this scattering is weaker than that of a helix. The ratio of the intensity of this scattering to that for $L = 2.0$ gives information about the average opening angle of the fan, $\theta$, figure 1. The scattering from the helifan is more complex. The components of the moments perpendicular to the magnetic field oscillate in a similar way to those of a helix and so the scattering from these components is centred on $L = 1.75$ and 2.25. The components of the moments parallel to the magnetic field have a ferromagnetic component and further oscillating components that produce scattering near $L = 1.67$ and 1.83.

In these calculations we have assumed that the ideal magnetic structures are undisturbed by the crystal field or other interactions. Distortions of these structures give rise to harmonics of the scattering and these are observed for bulk holmium. In the superlattices the experiments are more difficult because the mass of magnetic material in the samples is less and because the scattering from an SL is more complex than that from bulk material. Consequently we did not attempt to measure the distortions of the basic structures.

The results shown in figure 2 demonstrate that the different types of magnetic structure can be distinguished from an inspection of the scattering. The helical structure gives scattering only near the wave-vector of the helix, modulo a reciprocal lattice vector. The scattering from a ferromagnetic phase occurs only near reciprocal lattice vectors. The fan structure gives scattering near both positions and the helifan weaker scattering at the Bragg reflections and additional scattering between the Bragg reflections and the helical magnetic scattering.

The scattering from an ideal SL is the product of the block form factor discussed above and shown in figure 2 with the reciprocal lattice of the magnetic structure. The latter consists of a series of 'delta' functions separated by the reciprocal lattice vector of the SL, $\tau$, where $\tau = 2\pi/D$ with $D$ the block repeat length. The magnetic structure may also differ from the crystallographic structure of the SL because the phase of the magnetic structure may increase regularly from one block to the next by a phase angle $\Phi$ that is not necessarily a multiple of $2\pi$. The extent to which this phase angle differs from a multiple of $2\pi$ can be obtained from the

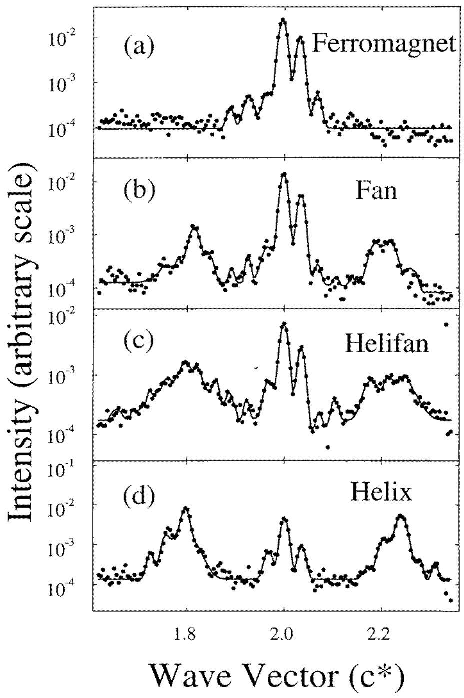


**Figure 3.** The neutron scattering from (a) a ferromagnetic phase $H = 3$ T and $T = 4$ K, (b) a fan phase $H = 3$ T and $T = 60$ K, (c) a helifan phase $H = 2$ T and $T = 50$ K and (d) a helix $H = 1$ T and $T = 30$ K. The solid lines are fits to a series of Gaussians.

difference between the positions in wave vector of the magnetic and crystallographic Bragg reflections.

The experimental data were analysed by fitting a series of Gaussian distributions to the peaks observed in the experiments as illustrated in figure 3. The wave vectors of the peaks determine the block repeat length, $D$, and the block phase angle, $\Phi$, while the intensities of the peaks are given by the block structure factors. The intensities were fitted to the expressions for the block structure factors by varying the magnitude of the magnetic moment on each plane, assumed constant throughout the holmium block, and the phase angle describing the direction of the moments on successive atomic planes. The crystallographic parameters were held fixed at the values found in the earlier x-ray measurements [6, 9]. In the case of the ferromagnetic scattering the magnetic scattering was obtained by subtracting the nuclear scattering measured at high temperatures from the total scattering. The width of the Gaussian peaks determines the coherence length of the different magnetic structures, $\xi = 2\pi/w$ after correction for the instrumental resolution.

## 4. The experimental results

A summary of the experimental results is provided by the phase diagram for the superlattice in an applied magnetic field and shown in figure 4. Before discussing the phase diagram however we shall discuss each of the phases in turn.

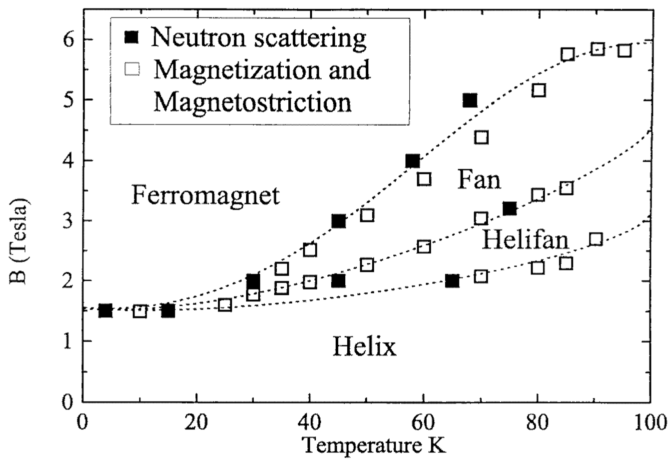


**Figure 4.** The phase diagram for the SL in an applied field. The ■ points are from the neutron scattering results, □ are from magnetization and magnetostriction [9].

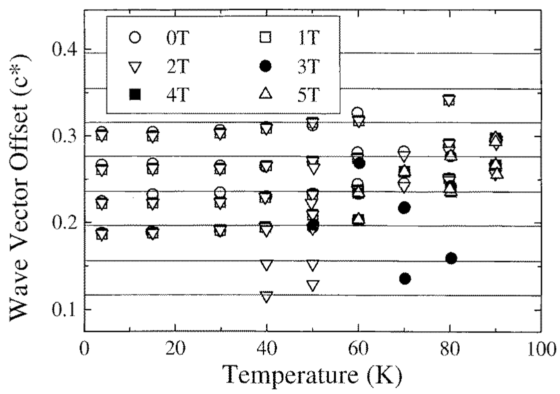


**Figure 5.** The wave-vector differences of the peaks in the scattering from the main (002) Bragg reflection. The solid lines show the positions of the chemical SL Bragg reflections.

### *4.1. The helical phase*

The magnetic structure is a basal plane helix for all temperatures below the magnetic ordering temperature, $T_c = 132$ K, in the absence of an applied magnetic field in agreement with the results found earlier [6]. The wave vectors of the peaks in the scattering are shown in figure 5 and for temperatures below about 40 K the positions are within the error the same as those of the chemical Bragg scattering from the SL. This shows that the turn angle of the helix over one SL period is a whole number of turns. In contrast, when the sample was studied previously [6] the turn angle of the helix over one SL period was 6.7 turns. The total turn angle in the holmium part of the SL block is about 4.6 periods at low temperature so there is an uncompensated magnetic moment in each block that can couple to the external magnetic field. This results in a reduction of the energy for a structure in which the phase angle for the whole block is an integral number of turns. This does not explain why the phase is a whole number of turns in the absence of a field or why the results obtained in this experiment differ

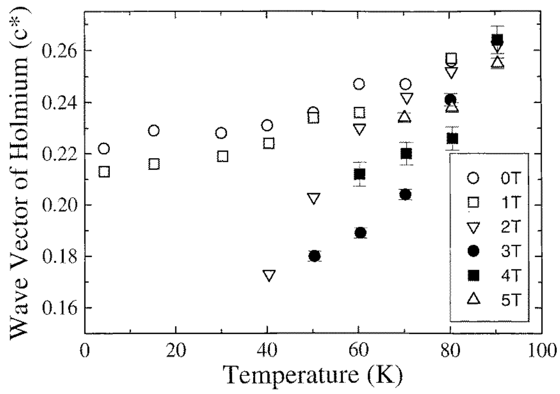


**Figure 6.** The wave vector describing the turn angle of the magnetic moments between successive holmium planes. The turn angles for the helix and helifan are similar to those in the absence of a field while those for the fan phase are significantly smaller.

from those obtained earlier, unless the residual field in the cryostat was sufficiently large to alter the magnetic structure. Above 40 K the positions of the peaks vary continuously with temperature so that there is very little tendency for the helical part of the structure to lock to the chemical SL. Possibly this is because the increasing turn angle reduces the total uncompensated moment on each holmium block. The intensities of the peaks were fitted to the model described earlier [6] with the structural parameters held fixed at the values determined before [9]. The results for the wave vector of the turn angle between successive holmium planes are shown in figure 6. At low temperatures the wave vector has the commensurate value, $2/9\boldsymbol{c}^*$ and the value steadily increases with increasing temperature towards the wave vector at the onset of magnetic ordering $2/7\boldsymbol{c}^*$.

The experimental results are similar when a field of 1 T is applied as shown for the wave vectors of the peaks and holmium turn angle in figures 5 and 6. One difference is that below 30 K there is a ferromagnetic moment that is on average $0.33 \pm 0.03$ of the total average magnetic moment. The helix must be considerably distorted from a simple helix by the applied field. Nevertheless the scattering is inconsistent with the scattering from a helifan phase because the scattering at the wave vectors corresponding to the helical scattering is considerably more than $1/2$ of the scattering from the ideal helical phase observed with no applied field. Above 30 K the wave vectors of the peaks in the scattering are no longer commensurate with the SL, figure 5, while the ferromagnetic moment has decreased by at least a factor of ten and the helical structure is consequently less distorted. The turn angle between successive holmium layers is slightly smaller than in the absence of an applied field, figure 6, while the corresponding turn angle for the yttrium layers, figure 7, is almost constant and independent of temperature. When the applied field is increased to 2 T the helical phase is no longer stable at low temperatures and becomes stable only above $45 \pm 5$ K. The holmium turn angle is very similar to that found at lower fields, see figure 6, while that of the yttrium is slightly larger. As the applied field is increased the temperature above which the helical phase is stable increases and is above 90 K for a field of 3 T and above. The holmium turn angles decrease as the field increases. Finally, the correlation lengths are shown in figure 8. The helical phase has a correlation length of about 11 SL periods for applied fields of 0 T, of $7.5 \pm 0.6$ periods for a field of 1 T and it reduces to $3.8 \pm 0.5$ periods when the field is raised to 2 T.

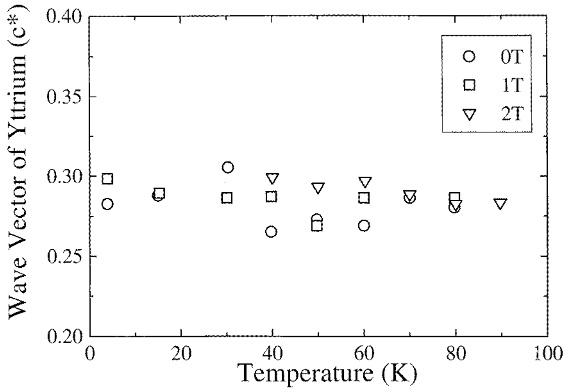


**Figure 7.** The wave vector describing the turn angle of the conduction electron spin density wave in the yttrium layers. The results are within error constant.

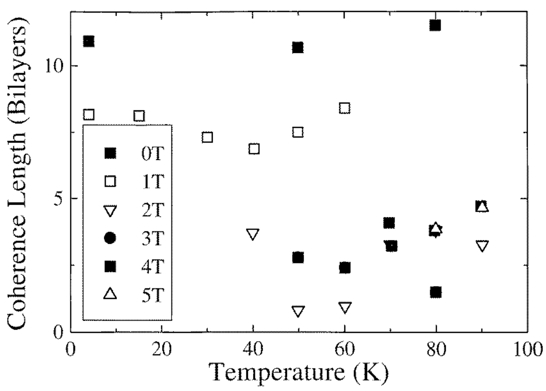


**Figure 8.** The coherence lengths of the modulated components of the ordered moments.

### *4.2. The ferromagnetic phase*

The ferromagnetic phase is characterized by scattering near the (002) Bragg peaks of the hcp structure and the neighbouring SL peaks and little scattering elsewhere. This type of scattering is generally observed at low temperatures when large fields are applied ($\geqslant 2$ T), for example, below $30 \pm 3$ K for a field of 2 T, below $47 \pm 3$ K for 3 T, below $58 \pm 2$ K for 4 T and below $70 \pm 3$ K for 5 T. At all fields, as might be expected, the ferromagnetic scattering shows long range order with a coherence length comparable with that of the chemical coherence of the SL. The ferromagnetic peaks always occur at the same wave vectors as those of the chemical structure suggesting that the yttrium layers do not play any role in the coherence of the ferromagnetic structure that is determined by the external field.

### *4.3. The fan phase*

The fan phase has scattering similar to that of both the ferromagnetic and helical phase scattering as shown in figure 3 and occurs next to the ferromagnetic phase at high field and low temperatures. The fan phase is not observed for applied fields below 1 T, but when the field is increased to 2 T the fan phase is observed for temperatures between $30 \pm 3$ and $45 \pm 3$ K. When the temperature is 40 K the average deviation of the magnetic moments from the field direction is 34°. The turn angle for the modulated component of the ordered moments is given by the wave vector $0.0173 \pm 0.008\boldsymbol{c}^*$ that within error corresponds to a turn angle of 30° between the holmium planes. The correlation length for this fan phase is $3.7 \pm 0.5$ SL periods.

When the magnetic field is increased to 3 T, the magnetic structure is a fan between $47 \pm 3$ and $75 \pm 3$ K. The mean angle of deviation away from the ferromagnetic direction increases from 9° at 50 K to 33° at 70 K. The wave vector of the modulated component of the holmium moment increases from $0.180\boldsymbol{c}^*$ at 50 K to $0.204\boldsymbol{c}^*$ at 70 K. The correlation length of the modulated component is $2.8 \pm 0.4$ SL periods while that of the ferromagnetic component is much longer and comparable to the chemical coherence length for the ferromagnetic components.

The fan phase is the stable magnetic structure above $58 \pm 2$ K for an applied field of 4 T. The wave vector of the modulated component increases from $0.212\boldsymbol{c}^*$ at 60 K to $0.264\boldsymbol{c}^*$ at 90 K, while the mean deviation from the applied field increases from 9 to 31°. The correlation length of the modulated component is $4.3 \pm 0.4$ SL periods. Finally, the results are essentially similar when the field is increased to 5 T except that the fan phase is stable only above $70 \pm 3$ K.

### *4.4. The helifan phase*

Holmium is the only rare earth for which the bulk is known to have a helifan phase. There are many different types of helifan phase [3], but in the bulk [4] and an alloy with yttrium [10] only one type of phase, helifan $3/2$, has been observed. In figures 3(c), 9(a) and 9(b) we show the scattering observed for a field of 2 T at 50 and 60 K and for a field of 3 T at 80 K. In all of these profiles the scattering from the modulated components of the ordered moments shows broad profiles with only little evidence of SL peaks. We estimate that the coherence length is between 1 and 1.5 SL periods, which is very short compared with the coherence length of the other magnetic phases. Since the difference in the energy of the various helifan phases is small, it is not surprising that in an SL the helifan phases hardly show any coherence in the structure from one SL block to the next. The scattering shown in figure 3(c) and 9 shows the features that are characteristic of helifan phases. Firstly, there is a small ferromagnetic component that corresponds to an ordered moment of much less than $1/2$ of the total ordered moment. Secondly, the scattering from the modulated components has two components: one at the wave vector, $q$, of the magnetic components perpendicular to the applied magnetic field, and another a wave vector of $2/3q$, which accounts for the spatial periodicity for the moments parallel to the magnetic field. This description is particularly good for the case of figure 9(b) but also describes figures 3(c) and 9(a). We are confident that at these temperatures and applied magnetic fields the magnetic structure of the SL is basically a helifan $3/2$ structure. We have not however succeeded in analysing the detail of helifan structure further because of the short coherence length.

### *4.5. Hysteretic effects*

The results described above were all obtained by changing the applied magnetic field at 5 K and then warming the samples. Experiments were also performed with other procedures to test whether the results depended on the past history of the sample. In particular the SL was prepared in an applied field of 3 T at 80 K by increasing the field from 0 T or by decreasing the field from 6 T while in both cases holding the temperature constant. The results are shown in figure 10(a) and (b), and can be compared with that obtained by heating which is shown in figure 9(b). The results obtained by heating and by reducing the field are very similar showing that a helifan

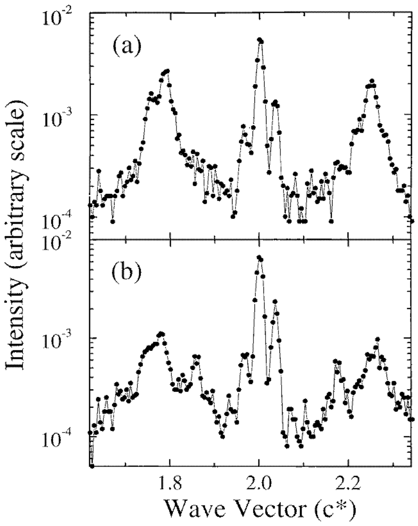


**Figure 9.** (a) The scattering observed from helifan structures for $H = 2$ T and 60 K and (b) $H = 3$ T and 80 K.

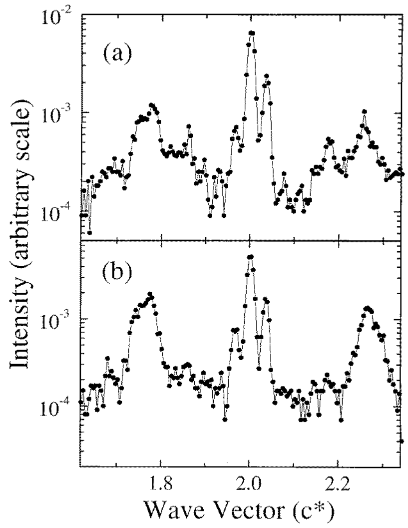


**Figure 10.** The scattering for $H = 3$ T and 80 K observed (a) when the field was reduced from 6 T and (b) when it was raised from 0 T, while in both cases the temperature remained constant.

type of structure is obtained with both procedures. In contrast, the results obtained by raising the field are somewhat different, and suggest that some of the sample may be in a fan phase.

After preparing the sample in a field of 3 T at 80 K in a fan phase, as described above, the SL was cooled and the scattering obtained at a series of different temperatures. The scattering that was observed at 70 K is very similar to that shown in figures 9(b) and 10(b) and is consistent with a helifan structure, while that observed at 60 and 50 K is characteristic of a fan phase. At 40 K the scattering is consistent with a ferromagnetic structure. In summary, the phase transition between the ferromagnetic and fan phases occurs at a temperature 43 ± 3 K, that between the fan and helifan occurs at 65 ± 3 K and that between the helifan and fan phases occurs at 75 ± 3 K. These transition temperatures are all below those found when the SL is heated and the difference possibly increases with increasing temperature.

These results are not at all unexpected because history dependent effects were observed during similar measurements on a holmium–yttrium alloy [10]. In that case the helifan phase was formed when the alloy was first prepared in a fan phase but was not found if the same region of the temperature field plane was entered from the helical phase. In the present case the results appear to be similar whether the helifan phase is entered from a fan phase either by heating or by reducing the field but if it is entered from the helix the structure is somewhat different and the transition temperatures are lower.

## 5. Summary and conclusions

The magnetic structures of a holmium/yttrium SL have been studied when a magnetic field is applied in the basal plane. The results show that the magnetic structures are based on the structures found when a magnetic field is applied in the basal plane of bulk holmium [3]. At low fields the magnetic structure is a helix which is coherent over many periods of the SL. With increasing applied field the helix becomes distorted, especially at low temperatures, while the coherence length of the structure decreases from over 10 SL periods to about 8 SL periods at 1 T and still less in a field of 2 T. This is possibly because the increasing ferromagnetic ordering spin scatters the helical conduction-electron spin-density wave and so decreases the coherence of the helical structure.

At larger fields, the scattering is consistent with a helifan 3/2 phase in which the coherence length of the modulated components is only slightly longer than a single holmium block length. There are many different helifan structures with similar energies [3] and so it is relatively easy for mistakes to arise in the helifan structure. Structures based on a fan phase are found at still higher fields and for these structures the ferromagnetic components of the moments have long range coherence while the modulated components are coherent over about 4 SL periods In the largest fields the moments are ferromagnetically aligned along the field direction.

These results are summarized in the phase diagram shown in figure 4 where they are also compared with measurements of the phase boundaries for the same SL made by magnetostriction and magnetization measurements [7, 11]. There is good agreement with the phase boundaries and the neutron scattering results provide a clear identification of the different structures. These results can be compared with the phase diagrams of bulk holmium [4] and of a holmium–yttrium alloy containing 70% of holmium [10]. The most striking aspect of the comparison is that at low temperatures the helix in bulk holmium is unstable when an external field of about 0.6 T is applied. In comparison for the SL (figure 10) a field of about 1.6 T is needed whereas for the holmium–yttrium alloy a field of about 3.5 T. Similar results have been found with magnetization measurements for $Ho_{19}Y_{12}$ and $Ho_6Y_9$ SLs. [8]. In both the SL and the alloy the wave vector describing the modulation of the helical structure is appreciably larger than for the bulk material. This enhances the stability of the helical phase compared with that of a fan phase. Furthermore yttrium has a larger peak in the conduction electron susceptibility than holmium [12] so that in the alloy the stability of the helical structure is further enhanced while the average coupling to the applied field decreases. In the holmium/yttrium SL the same type of mechanism may be present. The long-range coherence of the magnetic structure arises from the conduction electrons propagating coherently through the SL and this coherent propagation from the yttrium layers into the holmium layers enhances the stability of the helical phase within the holmium blocks.

It has also been argued that the stability of the helical phase for holmium/yttrium SLs compared with bulk holmium has its origin in the basal-plane clamping of rare earth blocks on the substrate [8]. The clamping decreases the magnitude of the magneto-elastic contribution to the energy of the ferromagnetic phase and so tends to stabilize the helical phase [8]. Recent results [7] suggest that the magneto-elastic coupling constants may be enhanced for the SL. Nevertheless it is difficult to understand why the clamping gives rise to a larger effect in the SLs and alloys than for an Ho film [8]. There is undoubtedly a correlation between the magneto-elastic effects and the wave vector of the helical structure [13], but further work is needed to determine whether the difference between the properties of the alloys, SLs and bulk arise from magneto-elastic effects or changes in the exchange interactions.

The phases with both oscillating and ferromagnetic moments have shorter correlation lengths for the modulated components at least in part because the ferromagnetic moments spin scatter the conduction electrons in the conduction electron spin density wave. The coupling of the uncompensated moments in the Ho blocks to the field may also reduce the coherence of the modulated structures [5] but this effect is likely to be small for a block with as many as 41 magnetic planes.

The helifan phase is not stable at low temperatures for the SL, as found for bulk holmium, and in contrast to the behaviour of the alloy. This is possibly because the alloy has a reduced average moment and behaves similarly to the bulk but with the phase diagram cut off when the moment reaches approximately 70% of the full holmium moment [10]. In the case of the SL we are concerned with the stability of the structures in the holmium blocks and so the phase diagram has a similar temperature scale to that of bulk holmium.

The SL showed some evidence of history dependent effects as also found in bulk holmium and the alloy thin film [4, 10]. This is not surprising given the small energy differences between the different phases and the possibility of pinning by impurities and imperfections.

Finally we have shown that neutron scattering techniques may be used to determine the subtle and complex structures which can occur when a magnetic field is applied to a magnetic SL. In this example all of the structures are based on those previously identified for bulk holmium [4]. The differences in the phase diagram from that of bulk holmium can be qualitatively explained as arising if the yttrium layers enhance the stability of a modulated magnetic structure by enabling in this case a conduction electron spin density wave to propagate throughout the SL.

## Acknowledgments

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## References

[1] Jensen J and Mackintosh A R 1991 *Rare Earth Magnetism. Structures and Excitations* (Oxford: Oxford University Press)
[2] Kitano Y and Nagamiya T 1964 *Prog. Theor. Phys.* **31** 1
[3] Jensen J and Mackintosh A R 1990 *Phys. Rev. Lett.* **64** 2699
[4] Jehan D A, McMorrow D F, Cowley R A, and McKintyre G J 1992 *Europhys. Lett.* **17** 553
[5] Erwin R W, Rhyne J J. Salamon M B, Borchers J, Sinha S, Du R, Cunningham J E, and Flynn C P 1987 *Phys. Rev.* B **35** 6808
[6] Jehan D A, McMorrow D F, Cowley R A, Ward R C C, Wells M R and Hagmann N 1993 *Phys. Rev.* B **48** 5594

[7] Ciria M, Arnaudas J I, del Moral A, Tomka G J, de la Fuente C, de Groot P A J, Wells M R and Ward R C C 1995 *Phys. Rev. Lett.* **75** 1634
[8] Conover M J, Fullerton E and Bader S D 1996 *Phys. Rev.* B **54** 1100
[9] Swaddling P P, Cowley R A, Ward R C C, Wells M R and McMorrow D F 1996 *Phys. Rev.* B **53** 6488
[10] Cowley R A, Ward R C C, Wells M R, Matsuda M, and Sternlieb B 1994 *J. Phys.: Condens. Matter* **6** 2985
[11] Ciria M, Arnaudas J I, del Moral A, de la Fuente C, Ward R C C and Wells M R 1998 *J. Magn. Magn. Mater.* **177** 1162
[12] Liu S H, Gupta R P and Sinha S K 1971 *Phys. Rev.* B **4** 1100
[13] Andrianov A V 1992 *JETP Lett.* **55** 666