Reynolds & Nicoll, 1976). The form of scattering in Fig. 5 is characteristic of the structure of clusters of this type. No detailed calculations have been carried out at present, though it may be noted that scattering from a branched polymer has a similar form (Kratochvil, 1972). If the clusters are approximated to Gaussian coils the radius of gyration corresponds to a mean end-to-end distance of 1000 Å.

The striking field dependence of the scattering observed for all alloys studied may be accounted for if the finite clusters behave as superparamagnetic entities at low temperatures. In zero magnetic field the average fluctuations of the spin components about their mean values of zero are equal and the small-angle scattering is isotropic. If a magnetic field is applied in the z direction, the fluctuation in the z component of spin must be reduced because of the partial alignment in that direction. This leads to anisotropic scattering. The diffuse scattering cross section in this case may be written in the form (Cywinski, Booth & Rainford, 1977*b*)

$$\frac{d\sigma}{d\Omega} \sim F^2(Q)\{[\langle S_x^2\rangle + \langle S_z^2\rangle - \langle S_z\rangle^2] + \cos^2\alpha[\langle S_x^2\rangle - \langle S_z^2\rangle + \langle S_z\rangle^2]\},$$

where S_x, S_z are spin components of the total *cluster* spin in the x and z directions, α is the angle between the scattering vector and the field direction, and $F(Q)$ is the *cluster* form factor. It can be shown that the coefficient of $\cos^2\alpha$ is positive for all values of the field, so that the anisotropic scattering may be written in the form

$$I(Q,\alpha) = A(Q) + B(Q)\cos^2\alpha,$$
$$B(Q) \geq 0,$$

generating a series of prolate ellipses. Furthermore, $A(Q)$ is found to be a decreasing function of H/T where $B(Q)$ increases with H/T to a shallow maximum and then decreases. This predicted behaviour with increasing field strength is seen in the contours given in Fig. 2, confirming the superparamagnetic behaviour of the clusters. A quantitative analysis of the scattering as a function of field will be presented elsewhere.

This behaviour should be contrasted with the diffuse scattering due to fluctuations in ferromagnetic long-range order, which is proportional to $(1-\cos^2\alpha)$ (Marshall & Lovesey, 1971). While these alloys are ferromagnetic, the volume fraction occupied by the infinite cluster is relatively small and much of the magnetic response is dominated by finite clusters which behave as superparamagnetic entities.

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Small-Angle Neutron Scattering from Rare-Earth Iron Alloys*

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Small-angle neutron scattering (SANS) has been used to investigate the onset of magnetic order and some aspects of the magnetic microstructure in a series of bulk amorphous rare-earth iron alloys prepared by DC rapid sputtering. SANS was also used to investigate crystalline (but atomically disordered) $TbFe_{1.5}Al_{0.5}$ and crystalline $TbFe_2$. The measurements were made for the most part on a two-axis spectrometer at a wavelength $\lambda = 2{\cdot}4$ Å with collimations of 20′–10′–10′. Some measurements were made on a three-axis spectrometer to obtain information on the inelasticity of the scattering.

The amorphous, binary alloys exhibit liquid-like diffraction patterns which can be explained by a model based on a random close packing of two unequal-size spheres (Rhyne, Pickart & Alperin, 1974). The alloys fall into two magnetic groups. The first, group 1, represented by $TbFe_2$, $HoFe_2$, $NdFe_2$ and $Tb_{0.018}Fe_{0.982}$ is ferrimagnetic but with a partial

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Table 1. *Summary of results*

	Amorphous			Crystalline	
	$TbFe_2$, $HoFe_2$, $NdFe_2$, $Tb_{0.018}Fe_{0.982}$	$GdFe_2$	YFe_2 $TmFe_2$	$TbFe_{1.5}Al_{0.5}$	$TbFe_2$
Magnetic order	Ferro	Ferro	Spin glass	Ferro	Ferro
$I(q)$ $T > T_c$	Lorentzian	?	Lorentz*	× ‡	
κ^{-1}	50–100 Å	?	~8 Å*	×	
H_c ($T \sim 4$ K)	Large (~30 kOe†)	~0	Small*	6 kOe	~0
$I(q)$ ($q > 0.02$ Å^{-1}) ($T \sim 10$ K)	$\sim q^{-3}$	~Const.	Lorentz*	$\sim q^{-3.1}$	$\sim q^{-3.5}$

* Only YFe_2 measured. † $TbFe_2$. ‡ × Not measured.

disorder of the rare-earth spins due to the random local anisotropy field acting on the rare-earth atoms. The Curie temperatures, T_c, are 385 K, 195 K, ~390 K and 245 K respectively (Alperin, Cullen & Clark, 1976; Rhyne, 1976). The second group, group 2, is represented by $GdFe_2$, a conventional ferrimagnet (here there is no anisotropy since Gd is in an S-state) with $T_c = 500$ K. For boths groups the T_c's are well below those of their crystalline counterparts (except that $Tb_{0.018}Fe_{0.982}$ has no crystalline counterpart). The Curie temperatures are also below the crystallization temperatures so that these materials remain amorphous up to and through T_c.

For the first group of alloys (see Table 1) the SANS intensities, $I(q)$ at scattering vectors q ($=4\pi \sin\theta/\lambda$) ranging from 0·02 to 0·14 Å^{-1} show a Lorentzian behavior. $I \propto 1/(\kappa^2 + q^2)$ for $T > T_c$ as expected for critical scattering from a ferromagnet. However, here the coherence length κ^{-1} instead of becoming infinite, as it does for a crystalline ferromagnet, remains finite with values ~50 to 100 Å (Pickart, Rhyne & Alperin, 1975; Pickart, Alperin & Rhyne, 1977). The scattering at the critical point, as determined from magnetization studies, is not sharp but rounded at T_c. The Lorentzian dependence even persists somewhat below T_c. These results suggest that conventional uniform long-range order does not occur in these amorphous alloys; instead a highly correlated form of cluster or strong super-paramagnetic order is suggested. $GdFe_2$ was difficult to measure (because of the high neutron absorption) but a broad hump in the scattering was observed in the region of T_c.

The third group of amorphous alloys represented by YFe_2 and $TmFe_2$ exhibit spin-glass-type behaviour with only short-range magnetic ordering (Pickart, Rhyne & Alperin, 1974). The q dependence of the intensity for YFe_2 is Lorentzian down to the lowest temperatures measured (4 K), yielding a very short correlation length $\kappa^{-1} \sim 8$ Å, consistent with the absence of long-range order.

For the group 1 amorphous alloys, intense SAS develops as the temperature is lowered. The scattering scales with the square of the magnetization, which indicates the effect to be entirely magnetic in origin. Inelastic scattering, multiple refractions at domain walls and multiple Bragg scattering can be ruled out, which leads to the conclusion that the scattering is due to diffraction by magnetic inhomogenities. At the lowest temperature the q dependence of the scattering is $\sim q^{-3}$ after correcting for resolution effects. Low-temperature SAS is also observed for YFe_2 and $TmFe_2$ but it is several orders of magnitude less intense and has a different q dependence. One possibility for the inhomogenieties is domain walls. Nevertheless, only in those alloys containing magnetic rare-earth atoms with magneto-crystalline anisotropy large enough to produce a large anisotropy-to-exchange-energy ratio will the wall be narrow enough to cause the diffraction effects. Thus $GdFe_2$ does not exhibit the low temperature SAS. Instead of domain walls an alternative explanation could be given in terms of a volume distribution of inhomogenieties in the magnetic order. The specific q^{-3} power law dependence observed is not understoood at this time. Nevertheless, it is interesting to note that since Porod's Law ($I \propto q^{-4}$), which is valid for any shape of non-interacting particles with random orientations, is *not* obeyed here, the conditions for its validity, namely $qL \gg 2\pi$ (where L is any dimension of the 'particle') are also not obeyed. Thus there must be dimensions $L \sim 2\pi/q_{max} \sim 40$ Å present in the distribution; a value not inconsistent with a narrow domain wall. (That there may also be some larger dimensions present is shown by a double, perfect-crystal experiment on amorphous $TbFe_2$ in the range $0.002 < q < 0.007$ Å^{-1}, which yielded a radius of gyration of ~800 Å.) If we consider the low-temperature SANS from crystalline $TbFe_{1.5}Al_{0.5}$ and $TbFe_2$ to have a common origin with that from the amorphous alloys, then domain walls offer a possible explanation of the observations. In the $TbFe_{1.5}Al_{0.5}$ case the atomic disorder leads to magnetic disorder not unlike the magnetic disorder in the group 1 amorphous alloys. It is not surprising therefore to observe a similar q-dependence of the low-temperature SAS for the two cases (see Table 1) which implies similar domain-wall widths. The presence of defects in the magnetic order provides pinning sites for the domain walls, which in turn give rise to the large low-temperature coercive forces (H_c) in these materials. The defect decreases the local exchange energy, further narrowing the wall over what it would be in a more defect-free case (*e.g.* crystalline $TbFe_2$). Thus we expect a somewhat wider domain wall for crystalline $TbFe_2$ with a consequent narrower SAS, as observed.

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