tering can be accomplished at a fixed temperature. The intensity off the analyzer as the crystal was rocked through the (110) position is shown in Fig. 1(c). This should be the strongest magnetic peak if the ordering is of the Cr_2O_3 type. The slight increase in the "flipper on" data can be accounted for by instrumental imperfections. For this reflection we find the ratio of magnetic to nuclear intensities is less than 5×10^{-3}, or $F_{111}^{mag}<0.020$. For the Cr_2O_3 magnetic structure with moments along the [111] direction, we find that $F_{110}^{mag}=0.84\ \mu f$. The same relationship is very closely true for a three-domain model in which the moments are all normal to [111] but rotated through 120° in going from one domain to another. Again assuming the free-ion form factor, we conclude that $\mu<0.03\ \mu_B$.

CONCLUSIONS

Our results are in agreement with those of Kendrick *et al.*[3] who found no evidence for the α-Fe_2O_3 magnetic structure. In addition, we can rule out the Cr_2O_3 magnetic structure. Our results indicate that the Ti moment at room temperature must be less than $0.03\ \mu_B$ in either of these structures. The small spurious peaks seen by Abrahams[2] are believed to be the result of simultaneous nuclear reflections.

The absence of magnetic order is in agreement with the results of Van Zandt *et al.*[4] who found no evidence for exchange fields in studying the magnetoresistance of Ti_2O_3 doped with vanadium. In explaining the conductivity of this material, one should avoid models which rely on the presence of antiferromagnetic order.

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Spin Directions in Pure Chromium*

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We have carried out a triple-axis polarized-neutron-beam experiment with polarization analysis of the final beam and magnetic fields to 15 kG applied to a pure Cr single crystal. The purpose was to determine whether the spin axis in the transversely polarized spin-density wave state (122°K–38.5°C) is confined to the cube edges or whether in sufficient fields it can be made to lie in an arbitrary direction (perpendicular to the wave vector). The experiments show unambiguously that the latter is so. At 25°C, it is slightly more difficult to confine the spins to a single 110 axis than it is to a single 100 axis. At lower temperatures this anisotropy is enhanced. These results along with our previous results for the field dependence of the cube-edge components using unpolarized neutrons have been analyzed in terms of two different models. Both models have the spins in all directions perpendicular to the wave vector of the spin-density wave. One is the model of thermal activation of small domains. The other considers a domain structure with wall motion. In both models ansiotropy and magnetic field influence the net number of spins in any given direction.

I. INTRODUCTION

Although the transversely polarized spin-density wave state which exists in pure chromium between the spin flip temperature (122°K) and the Néel point (38.5°C) has been extensively studied, the exact nature of the spin configuration in this state remains a puzzle. The experiment described here, using polarized neutrons and polarization analysis of the beam scattered from the (0,0,1-ϵ) reflection in a field-cooled crystal, shows that in the presence of a magnetic field the spin is *not* confined to the cube edges. This conclusion could not be obtained from our previous experiments with unpolarized neutrons.[1,2]

* The triple-axis work was done at the Phoenix Memorial Laboratory, the University of Michigan; the data shown in Fig. 2 was taken at Argonne National Laboratory under the auspices of the United States Atomic Energy Commission.

[1] S. A. Werner, A. Arrott, and H. Kendrick, Phys. Rev. **155**, 528 (1967).
[2] S. A. Werner, A. Arrott, and M. Atoji, J. Appl. Phys. **39**, 671 (1968).

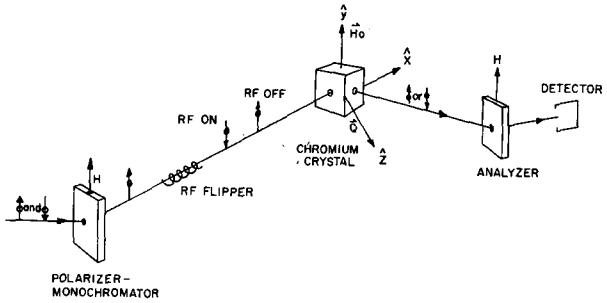

FIG. 1. Schematic diagram of the 3-axis, polarization analysis experiment used in determining the spin axis in chromium as a function of magnetic field.

II. DESCRIPTION OF EXPERIMENT

Figure 1 shows a schematic drawing of the experimental arrangement. The beam incident on the Cr crystal is polarized by the monochromator and its polarization can be reversed by the RF field. The spin-up (or spin-down) beam is then reflected by the Cr crystal [at $\mathbf{Q}=2\pi/a(0,0,1-\epsilon)$].

The neutron spin will either be flipped or not flipped depending on the configuration of the magnetization waves corresponding to the wave vector $\mathbf{Q}$. The analyzer is set to reflect only spin-up neutrons. Thus, when the RF field is off we are measuring the nonflip cross section ($\sigma_{\uparrow\uparrow}$) and when it is on we are measuring the spin-flip cross section ($\sigma_{\downarrow\uparrow}$). The x component of the magnetization wave contributes only to spin-flip scattering and the y component contributes only to nonflip scattering.

We have previously[2] shown that when a magnetic field is applied along $\langle 010\rangle$ the polarization of the fundamental magnetization wave (with $\mathbf{Q}$ along $\langle 001\rangle$) rotates toward $\langle 100\rangle$. In the present experiment this rotation of the polarization has the effect of increasing the spin-flip cross section at the expense of the nonflip cross section. The cross-section ratio $\sigma_{\downarrow\uparrow}/\sigma_{\uparrow\uparrow}$ (spin-flip/nonflip) is shown in Table I for two temperatures, 298° and 200°K.

If we now put the $\langle 110\rangle$ axis up (along the applied magnetic field $\mathbf{H}_0$) the ratio $\sigma_{\downarrow\uparrow}/\sigma_{\uparrow\uparrow}$ should be equal to 1 independent of magnetic field if the spins are confined to the cube edges. This was found not to be the case. In fact, at 298°K it is almost as easy to force the spins into a $\langle 110\rangle$ direction as into a $\langle 100\rangle$ direction. However, at 200°K, it is much more difficult to rotate the spins into a $\langle 110\rangle$ direction. Consequently, it appears that the anisotropy decreases rapidly with increasing temperatures, and may in fact go to zero at the Néel point.

III. DISCUSSION

In view of the fact that the rotation of the spin direction in an applied magnetic field is essentially reversible (with only a small amount of hysteresis and no resonance), a model for the "domain-wall" configuration must contain a "spring-back" or relaxation mechanism.

We discuss the results of this polarized beam experiment on chromium in terms of two "extreme" models. The one which focuses attention on the *domain* and ignores the *wall*, emphasizes the possibility of *thermal activation* of the spin orientation of small domains.[1,2] The second, which was suggested by Bindloss[3] to explain the torque measurements on AuMn, depends on the existence of *pinning sites* which require the spin to assume a definite (perhaps random) orientation at particular points in the crystal.

Thermal Activation

For an assembly of small domains whose spin orientation fluctuates due to thermal excitation, the elastic neutron scattering cross sections are

$$\sigma_{\uparrow\uparrow}\sim|M_y(\mathbf{Q})|^2=|\mathbf{M}(\mathbf{Q})|^2\langle\cos^2\beta\rangle \quad (1a)$$

$$\sigma_{\downarrow\uparrow}\sim|M_x(\mathbf{Q})|^2=|\mathbf{M}(\mathbf{Q})|^2\langle\sin^2\beta\rangle, \quad (1b)$$

where β is the angle between the magnetization $\mathbf{M}(\mathbf{Q})$ and $\hat{y}$ (which is $\perp$ to $\mathbf{Q}$ and $\|$ to $\mathbf{H}_0$).

These expressions represent an *incoherent sum* of the scattering from each domain. If we let θ be the angle between $\mathbf{M}(\mathbf{Q})$ and $\langle 010\rangle$ for a given domain and ϕ the angle between H_0 and $\langle 010\rangle$ then $\beta=\phi-\theta$, and the energy of a given domain of volume δV in the presence of a field consists of an (assumed four-fold) anisotropy term and a field-energy term,[1] namely

$$E(\theta)=[K\sin^2 2\theta+1/2\Delta\chi H_0^2\cos^2(\phi-\theta)]\delta V. \quad (2)$$

A calculation of the average values in Eqs. (1a) and (1b) over a Boltzmann distribution depends on two parameters

$$A=K\delta V/kT \quad \text{and} \quad B=\Delta\chi H_0^2\delta V/kT. \quad (3)$$

Using the data given in Table I for $\sigma_{\downarrow\uparrow}/\sigma_{\uparrow\uparrow}$ for the two orientations of the sample we obtain:

$$\text{at } 295°\text{K}: \quad A=0.47, \quad B=1.94$$

$$\text{at } 200°\text{K}: \quad A=2.1, \quad B=2.3. \quad (4)$$

Thus, according to this model the anisotropy constant

TABLE I. Ratio of $\sigma_{\downarrow\uparrow}/\sigma_{\uparrow\uparrow}$ for $\mathbf{H}_0=15$ kG.

Temperature	$\langle 100\rangle \| \mathbf{H}_0$	$\langle 110\rangle \| \mathbf{H}_0$
295°K	2.8±0.1	2.3±0.1
200°K	4.9±0.2	1.8±0.1

[3] W. Bindloss, thesis, University of California, Berkeley (1967).

K has decreased by a factor of about 4 in raising the temperature about 100°K.

Pinning Model

If the spin direction at certain points in the crystal is fixed the resulting configurations of the spins between two such sites will depend on the local balance of the torque resulting from the anisotropy, the applied magnetic field and the increase in exchange energy resulting from "twisting" the linear spin-density wave about an axis parallel to **Q**. If one assumes that this increase in exchange energy is proportional to the square of the angle of "twist", then the equation relating this angle to the position between the two pinning sites in a one-dimensional model is easily shown to be[4]

$$z/L=\int_{\theta_o}^{\theta(z/L)}\pm\left[g(\theta)-g(\theta_0)+\left(\frac{d\theta}{d(z/L)}\right)_0^2\right]^{-1/2}d\theta, \quad (5)$$

where

$$g(\theta)=x\cos^2(\phi-\theta)+y\sin^2 2\theta.$$

θ_0 is the angle of the spin at $z=0$. This equation must be solved subject to the condition that $\theta(z/L=1)$ is equal to the angle of the spin pinned at $z/L=1$. This model therefore depends on two parameters $x=L^2\Delta\chi H_0^2/2\lambda$ and $y=L^2K/\lambda$, where the increase in exchange energy has been written as $\lambda(d\theta/dz)^2$.

Because the polarization direction of the spin density wave must rotate in a correlated manner between the two pinning sites, the neutron scattering cross sections take the form of coherent sums, namely

$$\sigma_{\uparrow\uparrow}\sim|\mathbf{M}(\mathbf{Q})|^2\langle\cos\beta\rangle^2 \quad (6a)$$

$$\sigma_{\downarrow\uparrow}\sim|\mathbf{M}(\mathbf{Q})|^2\langle\sin\beta\rangle^2, \quad (6b)$$

where the averaging function that replaces the Boltzmann distribution is $p(\theta)=(dz/d\theta)$. We have solved Eq. (5) and performed the integrations indicated in (6a) and (6b) for several cases, the detailed results of which will be reported elsewhere.

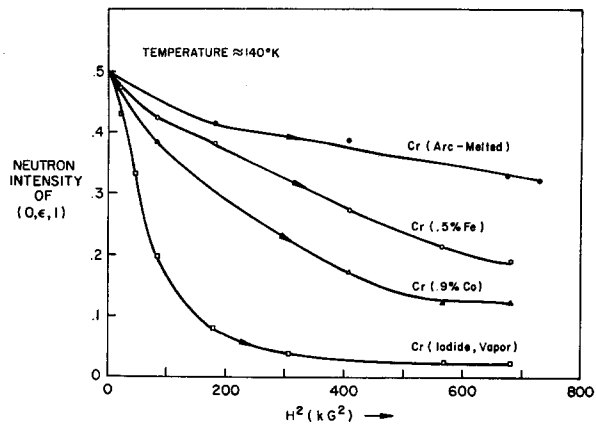

FIG. 2. The intensity of the $(0, \epsilon, 1)$ reflections as a function of H_0^2 for four different crystals in an unpolarized beam experiment. The field was applied along ⟨100⟩. In this experiment only spin-up neutrons are scattered, and the cross section is $\sigma_{\uparrow\uparrow}$ ($\sigma_{\uparrow\downarrow}=0$ for this orientation).

The important conclusion of these calculations is that for unpolarized neutrons, $(\sigma_{\downarrow\uparrow}+\sigma_{\uparrow\uparrow})$ is dependent on the anisotropy constant. Consequently, a temperature dependence of this cross section does not give the correct variation of $|\mathbf{M}(\mathbf{Q})|^2$ with temperature. The neutron scattering depends on the exact nature of the variation of spin orientation with position, $\theta(z/L)$, and consequently depends on the value of the anisotropy constant K at each temperature.

Support of this pinning model for Cr, in addition to the wide disparity of the results on the temperature dependence of $M(\mathbf{Q})$, is provided by the data in Fig. 2. The spin is more difficult to reorient with a field in the less perfect crystals, indicating that the pinning sites are more frequent, thus requiring more torque to rotate a spin against the exchange field.

[4] Equation (5) is obtained by performing a variation on the total energy of the wall in a manner analogous to the classical treatment of a ferromagnetic wall.