cal formula. If $\mu_{\perp i} = eD_{\perp i}/kT_i$, where $D_{\perp i}$ is the enhanced (Bohm) value, S becomes so large that no fit with experiment is possible. Thus an enhanced mobility is inconsistent with the assumptions we have already made.

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[*] This research was supported by the U. S. Atomic Energy Commission.

[1] A complete paper including the experimental details is in preparation.

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POLARIZED NEUTRON STUDY OF ANTIFERROMAGNETIC DOMAINS IN MnF_2[†]

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A direct method of "seeing" antiferromagnetic domains which has not been employed heretofore is to utilize Bragg scattering of polarized neutrons from single-crystal specimens. The simplicity of this method and its sensitivity to the domain apportionment have allowed us to study the spatial distribution, temperature dependence, and response to magnetic annealing fields of the antiferromagnetic domains in MnF_2. In contrast to the recently reported technique of detecting antiferromagnetic domains by the electrically induced shift of the fluorine nuclear magnetic resonance,[1] the neutron diffraction method reported here allows one to make measurements in the very interesting region just below the Néel temperature.

A polarization dependence of the neutron scattering can be described most conveniently as a departure from unity of the ratio of the reflected intensities for incoming neutron beams of opposite polarization, i.e., $R = I_+/I_- = (N+M)^2/(N-M)^2$, where N and M are total nuclear and magnetic structure factors, respectively. For $R \neq 1$ it is clear that neither N nor M can be zero. If this condition is to be satisfied for a reflection from an antiferromagnetic structure, magnetic atoms with opposite spins must be related by one of the symmetry elements of the space group and not by a lattice translation; this requirement is satisfied for the structures shown schematically in Figs. 1(a) and 1(b) but not for the structure shown in Fig. 1(c). Secondly, there is no polarization dependence if the nuclear and magnetic structure factors are 90° out of phase. This is true when the magnetic atoms that are related by a center of symmetry have oppositely directed spins, as, for example, the case of Cr_2O_3. In MnF_2 the two Mn atoms that form the antiferromagnetic sublattices are related by a translation of $\frac{1}{2}, \frac{1}{2}, \frac{1}{2}$, but the local symmetry of the F atoms about these two sites is orthorhombic and differs by a 90° rotation about the [001] axis. Because of these

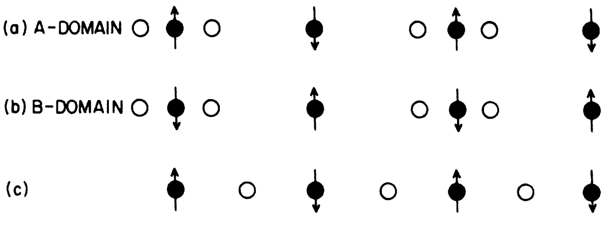

FIG. 1. One-dimensional antiferromagnetic arrays. The solid and open circles denote magnetic and nonmagnetic atoms, respectively; the arrows give the spin direction. Cases (a) and (b) will each scatter neutrons of opposite polarization differently. Case (c) is insensitive to neutron polarization.

translational and rotational properties the above conditions are met.

A uniaxial antiferromagnetic crystal such as MnF_2 may in general contain domains of types A and B [Fig. 1(a) and 1(b)]. If one denotes by α the fraction of the exposed volume that is an A-type domain then R will depend upon α in such a way that R approaches unity as α goes to 0.5. One can then calculate α knowing R.

The experiments were performed for the most part on a single crystal of MnF_2, 1.5 mm in diameter and 3.3 mm in length, which was cut from a large boule grown by J. W. Stout of the University of Chicago, and aligned with the c axis in the direction of the neutron polarization. The (210) reflection was chosen for study because for this reflection $N \cong M$ at 4.2°K and hence R will depend sensitively on α. When cooled to liquid helium temperature in the 20-oersted magnetic field necessary to maintain the neutron polarization, a sizable portion of the crystal was found to be a single domain, while other regions of the crystal showed a 1:1 mixture of the A and B types. The domains were observed by scanning the crystal with a cadmium slit approximately 1 mm wide. Figure 2 illustrates the variation in α along the long axis of the crystal; the α value for the crystal as a whole in this case was $(80 \pm 5)\%$. According to Li,[2] the retention of some domain structure at low temperatures implies that the domain walls are pinned down to lattice imperfections, since they would otherwise be unstable.

The actual domain distribution was found to be determined by the magnetic field applied to the crystal as it was cooled through the Néel point. A given cooling field, even as weak as 5 oersteds, always produced the same distribution on subsequent recoolings. Reversing this bias field changed the domain type from A to B without changing the distribution. However, the spatial distribution of the domains as well as the value of α for the whole crystal was found to vary on repeated coolings in the earth's field. These effects suggest an interaction with net moments on the domain walls as a mechanism for fixing the walls at imperfections, and are probably related to the observations by Borovik-Romanov[3] on the piezomagnetic moment of MnF_2.

We have also investigated the change in the detailed and over-all domain distribution as the crystal was warmed up through the Néel point. In order to obtain an estimate of the relative domain population at temperatures above liquid helium it is necessary to establish the temperature dependence of the sublattice magnetization. This was done by using the purely magnetic (100) reflection as a standard. Figure 3 shows the ratio

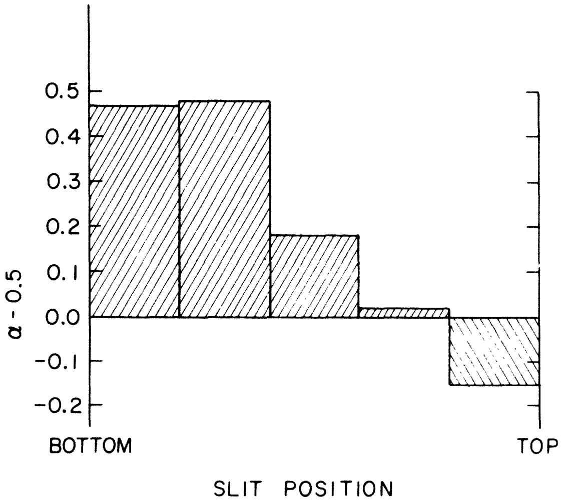

FIG. 2. Domain pattern in the MnF_2 crystal cooled to 4.2°K in a 20-oersted field. The deviation of the distribution from an equal proportion of the two domain types is plotted as a function of the Cd slit position, each bar corresponding to a shift of $\frac{1}{32}$ of an inch. The bottom of the crystal is nearly single domain, while the negative region at the top is preponderantly of the opposite type.

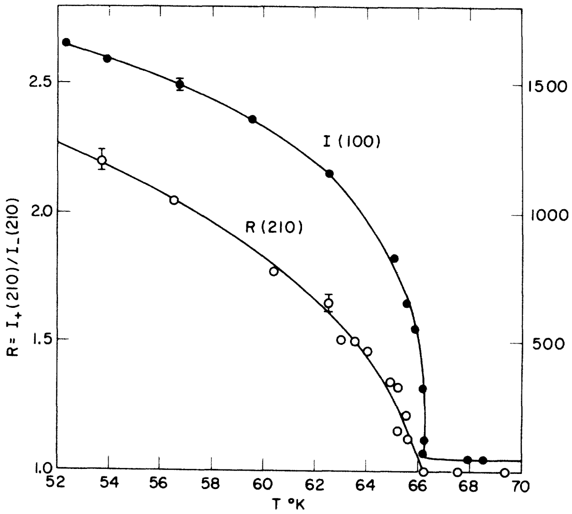

FIG. 3. The polarization ratio I_+/I_- for the (210) reflection and the intensity of the (100) reflection as a function of temperature for the crystal cooled in a 20-oersted field. About one-half the (100) intensity above T_N is background.

of the intensities I_+ and I_- of the (210) reflection and $I(100)$ as a function of temperature for the crystal cooled in a 20-oe field. The (100) reflection shows the disappearance of long-range order at $T_N = 66.2 \pm 0.5°\mathrm{K}$ and the persistence of some short-range magnetic scattering above this temperature. An analysis of the observed polarization ratio, making use of the experimental sublattice magnetization, indicates that the domain distribution remains essentially constant from 4.2°K up to within a few degrees of the Néel point. The details of the domain behavior at temperatures immediately below the Néel point are difficult to establish with precision because of the large changes in the sublattice magnetization occurring within this temperature region and the uncertainty in estimating the proper extinction corrections. However, the observation of $R \neq 1$ up to the Néel temperature suggests that a one-to-one proportion of antiferromagnetic domains is not reached up to the point at which the long-range ordering of the manganese spins disappears.

An unusual feature of the results was the presence of large primary extinction effects, of the type discussed by Hamilton.[4] The size of these effects could be correlated with the degree to which a particular region of the crystal was single domain. It therefore appears that it is the local perfection of the crystal, i.e., the size of the mosaic blocks, that establishes the size of the antiferromagnetic domains.

A second crystal, grown by J. W. Nielsen of the Bell Telephone Laboratories, yielded results which were in every way similar to those obtained from the first crystal, except that the domains were distributed more uniformly in this case.

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FERMI SURFACE OF ALLOYS

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The Fermi surface of some metals has been extensively investigated experimentally and its shape has been rather definitely established.[1] In the case of noble metals (Cu, Ag, Au), all the data clearly indicate that the Fermi surface of these metals is not a simple sphere but that it bulges out in the [111] direction and touches the {111} boundaries of the first Brillouin zone. However, in the case of alloys, the situation is not very clear. In the first place, we lack a definite theoretical knowledge of what we mean by the Fermi surface of an alloy although we would expect in general that a Fermi surface similar to that of a pure metal should exist. At the same time, the direct experimental measurement of the Fermi surface of alloys is yet unpractical, because the experimental techniques of these measurements usually require samples with a long mean free path of electrons which can only be attained in highly pure metals.

There is still a series of experimental methods or facts such as the measurement of ordinary transport properties, optical properties, electronic specific heat, etc., which indirectly indicate the shape of the Fermi surface of alloys. However, the interpretation is not yet consistent. Among these, the interpretation of the Hume-Rothery rules based on the Brillouin zone structures is interesting. As is well known, there is too much regularity in the electron-atom ratio at which a definite phase boundary appears in different alloys, for the empirical Hume-Rothery rule to be written off as a mere coincidence. However, the original interpretation of Jones[2] in terms of a spherical Fermi surface has lost its ground with our present knowledge about the shape of the Fermi surface. Some theoretical attempts appeared in order to reconcile this difficulty. For example, Cohen and Heine[3] suggested, particularly for Cu alloys, that the band gap