left at position G, we conclude that Auger decay of the hole [see point (7)] is a negligible effect.

(c) Above peak G, electron transitions into one-electron continuum states have kinetic energies high enough to suffer energy loss according to point (4); therefore many low-energy electrons are ejected into this region of the spectrum as may be seen from the different shapes of the spectra at $U_R = 0$ V and $U_R \geqslant 2$ V. But also electrons with their original energies are left, as can be seen from the step at $U_R = 11$ V according to point (3).

(d) At $U_R = 11$ V, mainly a background of electrons ejected from the valence band is left for $h\nu < 45$ eV. This reflects the intensity distribution behind the exit slit according to point (1). The only structure left is the strong exciton B superimposed on this background.

We have given one possible consistent interpretation of our results which appears to us to be the most plausible within the frame of present knowledge on band structure and excitons. Of course, we are aware that this has to be tested by extending photoemission experiments to higher retarding voltages and other substances.

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[1]R. Haensel, C. Kunz, T. Sasaki, and B. Sonntag, Phys. Rev. Letters 20, 1436 (1968).

[2]T. Sagawa, in Soft X-Ray Band Spectra and the Electronic Structure of Metals and Material, edited by D. J. Fabian (Academic Press, Inc., New York, 1968), p. 29.

[3]T. Sagawa et al., J. Phys. Soc. Japan 21, 2587 (1966).

[4]Y. Iguchi et al., Solid State Commun. 6, 575 (1968).

[5]T. Miyakawa, J. Phys. Soc. Japan 17, 1898 (1962).

[6]J. C. Hermanson, Phys. Rev. 177, 1234 (1969).

[7]R. Haensel, G. Keitel, P. Schreiber, and C. Kunz, to be published.

[8]R. Haensel, C. Kunz, T. Sasaki, and B. Sonntag, Appl. Opt. 7, 301 (1968).

[9]K. Teegarden and G. Baldini, Phys. Rev. 155, 896 (1967).

TRANSFORMATION TO FAN SPIN STRUCTURE BY EXTERNAL FIELD IN FERROMAGNETIC MnP

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Neutron-diffraction studies have shown that ferromagnetic MnP undergoes a transformation to a periodic fan structure by an external magnetic field. The magnetic moment in the fan is higher than that in the ferromagnetic state. Both the moment and the period of the fan decrease with increasing applied field.

Manganese phosphide is ferromagnetic below 291.5°K, but it transforms to a metamagnetic phase at 50°K.[1] In the ferromagnetic state the crystals have an orthorhombic structure ($a > b > c$ for convenience) with the easy magnetization axis along the c direction. The magnetic structure at 4.2°K was found by neturon diffraction to be a spiral with propagation vector $0.112 \times 2\pi/a$ along the a axis.[2,3] The envelope of the spiral was suggested to be anisotropic. The average magnetic moment per Mn atom in the bc plane was estimated to be $1.58\mu_B$, which is greater than the ferromagnetic moment of $1.29\mu_B$.

Recent investigation of magnetic and electric properties of single crystals has suggested[4] that the ferromagnetic structure above 50°K transforms to a periodic fan structure when an external magnetic field is applied along the b axis. This paper is concerned with a neutron diffraction study of this transformation.

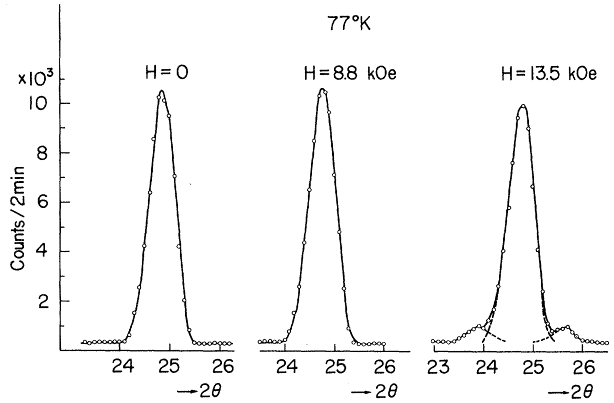

FIG. 1. (200) reflections in three different magnetic fields applied in the [010] direction.

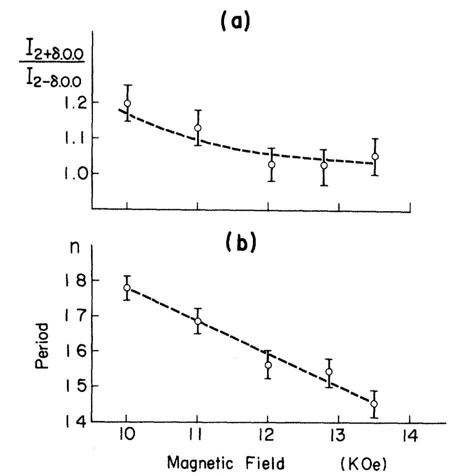

FIG. 2. (a) The ratio of a pair of satellites $I_{2+\delta,0,0}/I_{2-\delta,0,0}$ and (b) the period of fan as a function of applied fields.

The crystal used in the experiment was grown by the Bridgman method. Neutron-diffraction studies at room temperature confirmed that the crystal structure observed is consistent with the crystal parameters hitherto reported.[5] The 3-mm-diam spherical specimen was mounted in a special cryostat within an electromagnet that was installed on the neutron-diffraction spectrometer of the Institute for Solid State Physics at JRR-3 Reactor. The specimen mounting allowed rotation about the crystallographic b axis. By blowing liquid nitrogen directly against the crystal, the desired low temperature was obtained. The (200) reflection was measured with θ and 2θ scans at 77°K as a function of various magnetic fields applied in the b axis.

Figure 1 shows the reflected lines at 77°K in three different fields. This figure shows a pair of satellites which appear around the main peak when the external field exceeds 10 kOe. The intensity of the central reflection does not change until 10 kOe is reached but it decreases by about 9% with the appearance of the satellites. The second harmonics were also found to exist with the intensity about 8% of that of the first ones. This result indicates that in the magnetic field the ferromagnetic moments are rotated in the bc plane towards the external field until the field reaches 10 kOe and then the spin structure transforms to the fan with periodicity along the a axis. The period of the fan is estimated from the distance between the pair of satellites and varies linearly with the external field as shown in Fig. 2(b). It is noted that the period is almost twice as large as that of the spiral at 4.2°K. The ratio of the intensities of the first satellites $I_{2+\delta,0,0}/I_{2-\delta,0,0}$ is also plotted in Fig. 2(a). The satellites have almost the same intensity above 12 kOe, in contrast to the ratio 1.465 ± 0.005 observed for the spiral.[2] This ratio is a function of the phase angle φ between the magnetic moments on a pair in the bc plane separated by $0.1a$.[2] The result suggests that these moments align almost parallel with each other in the fan structure if the external field is higher than 12 kOe.

The magnetic contribution in the (200) reflection was evaluated by subtracting the nuclear reflection. The nuclear reflection was determined by extrapolation from its room temperature value, using an appropriate temperature factor. The intensity was also corrected for secondary extinction. The ferromagnetic moment at 77°K was estimated to be $(1.20 \pm 0.05)\mu_B$ per Mn atom, which is consistent with the reported spontaneous moment at 0°K. In Fig. 3 are plotted the intensities of the total magnetic reflection I_t, the (200) magnetic reflection I_c, as well as the pairs of satellites $I_{2-\delta,0,0}+I_{2+\delta,0,0}$ and $I_{2-2\delta,0,0}+I_{2+2\delta,0,0}$ as a function of the applied field. They are normalized to I_0, the magnetic reflection in no field. It is noted that the intensities of the total reflection are about 1.5 times greater than that in the ferromagnetic state. This suggests that the magnetic moment μ_f in the fan structure is about 1.2 times greater than the ferromagnetic moment μ_0.

The transformation from ferromagnetism to the fan caused by the magnetic field was first predicted in the theory of Kitano and Nagamiya.[6] In this theory, a system consisting of a great number of equivalent ferromagnetic layers is treated and the angle θ_n of spins on the nth layer in the fan is assumed to be modulated by a relation

$$\sin\tfrac{1}{2}(\theta_n - \psi) = x^{1/2}\cos(nq + \alpha), \qquad (1)$$

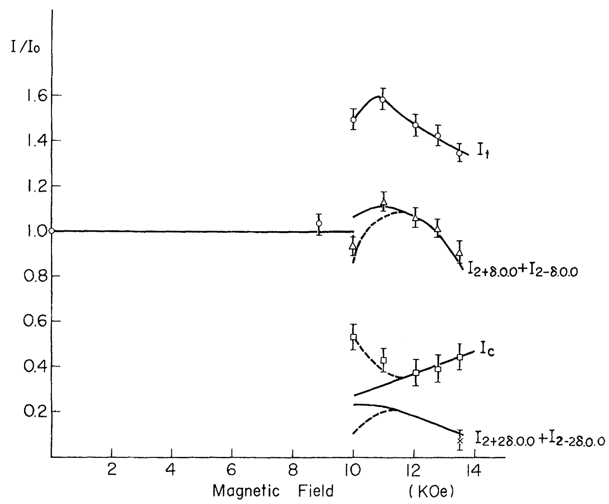

FIG. 3. Integral intensities of total reflection I_t, (200) magnetic reflection I_c, and pairs of satellites $I_{2+\delta,0,0}+I_{2-\delta,0,0}$ and $I_{2+2\delta,0,0}+I_{2-2\delta,0,0}$ plotted as a function of applied fields. They are normalized to I_0, a magnetic reflection in zero field. Solid and broken lines for satellites were calculated using the moment μ_f and the fan amplitude x determined experimentally.

where ψ is the angle between the field direction and the center of the fan. Assuming that μ_f does not depend on the crystallographic direction, the intensities of various reflections from this fan structure are calculated to be

$$\begin{aligned} I_c &= K|f(\theta_B)|^2\mu_f^2(1-x)^2, \\ I_{2\pm\delta} &= K|f(\theta_B\pm\Delta)|^2\mu_f^2x(1-\tfrac{3}{8}x)^2, \\ I_{2\pm2\delta} &= K|f(\theta_B\pm2\Delta)|^2\mu_f^2\tfrac{1}{4}x^2, \\ I_t &\approx K|f(\theta_B)|^2\mu_f^2, \end{aligned} \tag{2}$$

where $f(\theta)$ is the magnetic form factor, and K, a constant. The intensity of the third harmonic is of the order of magnitude of x^3 and can be therefore neglected.

As the magnetization in the field direction M is given by $M=N\mu_f(1-x)\cos\psi$, the normalized magnetization M/M_0 in the fan structure is related to the central reflection I_c/I_0 by

$$\left(\frac{M}{M_0}\right)^2=\frac{I_c}{I_0}\cos^2\psi. \tag{3}$$

$(M/M_0)^2$ was determined experimentally using the same crystal and are traced in Fig. 3 by a solid line to compare with I_c/I_0. Above 11.5 kOe the values are equal. Therefore the center of the fan coincides with the field direction above this field. The angles ψ in the fields of 10 kOe and 11 kOe are estimated to be 45° and 22.5°, respectively.

By using the amplitude of the fan x and the moment μ_f estimated from M/M_0 and I_t, respectively, the intensities of the satellites are calculated from Eq. (2). The results are shown in Fig. 3 by the solid and broken lines. The former lines were calculated for the case of $\psi=0$, while for the latter lines, the experimentally determined angles were adopted. The agreement between the observed values and the calculated ones are found to be satisfactory. Therefore we conclude that the simple fan structure defined by Eq. (1) is closely realized in MnP. The model that the magnetic moment does not depend appreciably on the crystallographic direction seems to be good. This is contrary to the spiral structure at 4.2°K.

In conclusion, when the external field is applied to the b axis at 77°K, the ferromagnetic spin structure transforms to the fan, the center of which is deviated by 45° from the field direction at 10 kOe. The central axis coincides with the field direction, if the field exceeds 12 kOe. The maximum deviation of the spin from the central axis is 45° at 12 kOe. The magnetic moment per Mn atom in the fan structure is greater than that in the ferromagnetic state. It takes the maximum value of $(1.59\pm0.05)\mu_B$ at 11 kOe and decreases with increasing the field, presumably tending to the ferromagnetic moment of $1.22\mu_B$. The period of the fan also decreases linearly with increasing the field.

The transformation to the fan structure by the field can be understood qualitatively by the theory of Kitano and Nagamiya. They have, however, assumed that both the moment and the period are constants of the substance, which does not appear to be the case for MnP. Further refinement of the theory is necessary to account for these behaviors.

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[1]E. E. Huber, Jr., and D. H. Ridgley, Phys. Rev. 135, A1033 (1964).

[2]J. B. Forsyth, S. J. Pickart, and P. J. Brown, Proc. Phys. Soc. (London) 88, 333 (1966).

[3]G. P. Felcher, J. Appl. Phys. 37, 1056 (1965).

[4]T. Komatsubara, T. Suzuki, and E. Hirahara, J. Phys. Soc. Japan 26, 208 (1969).

[5]S. Rundquist, Acta Chem. Scand. 16, 287 (1961).

[6]Y. Kitano and T. Nagamiya, Progr. Theoret Phys. (Kyoto) 31, 1 (1964).