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Spin-Waves in MnP

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Spin-waves in MnP have been measured by means of neutron inelastic scattering at various temperatures. Dispersion relation along *a*-axis exhibits anomalous wave vector and temperature dependences, while the quadratic *q* dependence was observed along both *b* and *c*-axis. The characteristic feature of the spin-wave dispersion relations agree qualitatively with those predicted on analogy with rare earth metals.

The 3*d* intermetallic compound MnP which is ferromagnetic between 291 K and 47 K and helimagnetic below 47 K has been considered as a localized spin system and the *s-d* model was applied to interpret the experimental results. Recently, however, it has been suggested that MnP should be a quasi-localized spin system from the band structure calculation[1] and several experimental results; an enhancement of the paramagnetic moment ($\mu_{para}=2.9\pm0.6\,\mu_B$[2]) compared with the low temperature saturation moment ($\mu_{sat}=1.33\pm0.01\,\mu_B$[3]), large γ value in the low temperature specific heat[4] and photoelectron spectra.[5] Spin-waves in MnP have already been measured in a small-q region at temperatures below 150 K by Tajima *et al.*[6] Adopting a Heisenberg model they deduced nearest neighbour effective inter-planar exchange interaction (J_1) and next-nearest neighbour one (J_2) along the *a*-axis (the direction of propagation of screw in the helimagnetic state) and concluded that the ferro-screw transition at 47 K is caused by the slight change of the ratio of J_2/J_1 with temperature. Furthermore with respect to the multicritical point or the Lifshitz point, measurements of spin-waves along the *a*-axis under magnetic field along the *b*-axis were performed by Yoshizawa *et al.*[7] In this letter, we report ferromagnetic spin-waves of MnP along three principal axes at relatively small-q region and discuss its characteristic feature comparing with a model dispersion postulated previously.[8]

MnP has a orthorhombic, distorted NiAs structure with four Mn atoms and four P atoms in a unit cell. The lattice parameters are $a=5.916$, $b=5.260$ and $c=3.173$ Å at room temperature. In the ferromagnetic state spins are parallel to the *c*-axis, while in the helimagnetic state the screw propagation vector $\boldsymbol{Q}_h(=0.117\boldsymbol{a}^*)$ is parallel to the *a*-axis.

For sample preparation, 99.999% P flakes and powdered 99.99% Mn were mixed and sealed in a quartz tube. The mixture was heated gradually and kept at 900°C for two days. Then single crystal of MnP was grown by Bridgman method and purified by zone refining. The ferromagnetic spin-waves (; at temperatures above 47 K) along the three principal axes have been measured by means of neutron inelastic scattering technique using triple-axis spectrometer TUNS installed at JRR-2, Tokai Establishment JAERI. The results together with data obtained by previous measurements[6] are shown in Fig. 1. Examples of temperature dependence of constant-*E* spectra are shown in Fig. 2. Along the b^* and c^* direction the spin-wave dispersions show q^2 dependence at small-q region, while along the a^* direction the dispersion shows unusual q-dependence as shown already in refs. 1 and 2. The spin-wave stiffness constants at 150 K are 145 and 70 meVÅ^2 for the b^* and c^* direction

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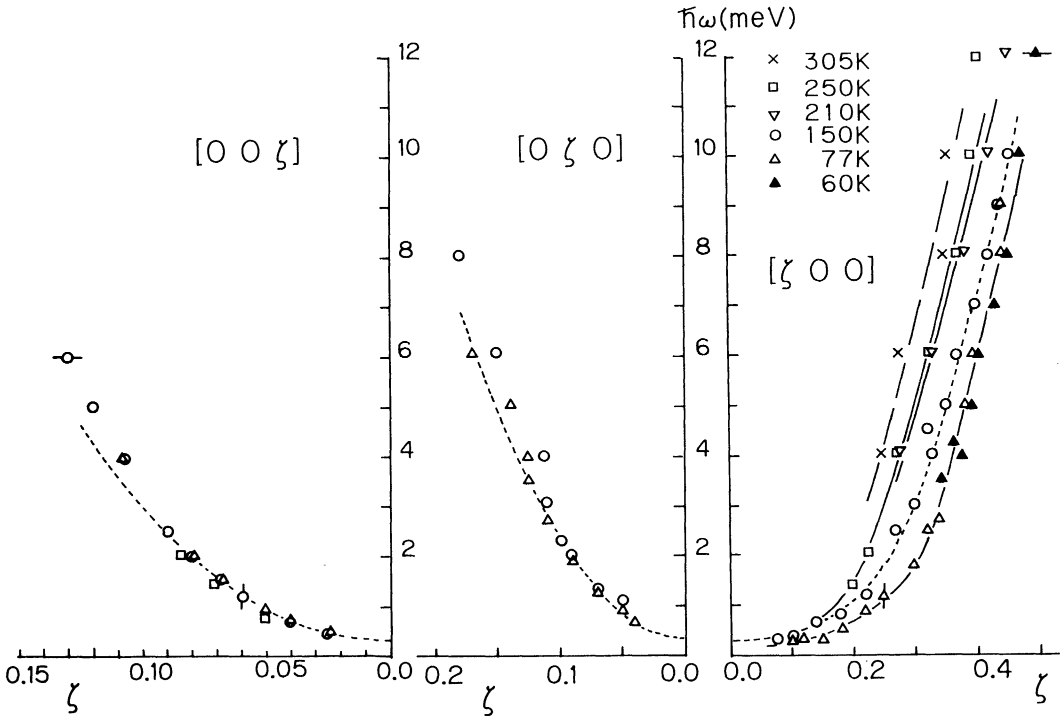

Fig. 1. Spin-wave dispersions along a^*, b^* and c^* directions. The solid lines are guides to the eye. The dotted lines represent the relation of $\hbar\omega_a=86q_a^3+\Delta$, $\hbar\omega_b=145q_b^2+\Delta$ and $\hbar\omega_c=70q_c^2+\Delta$ with $\Delta=0.35$ for a^*, b^* and c^* directions respectively.

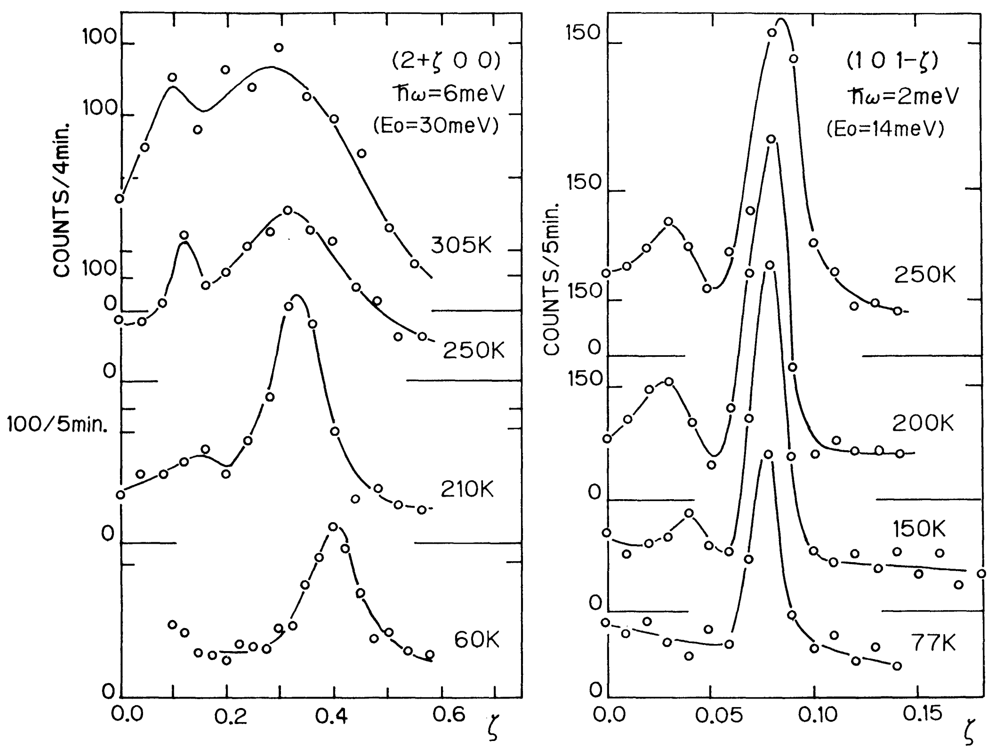

Fig. 2. Temperature dependence of spin-wave spectra obtained by constant-E scans.

respectively. The dispersion along the a^* direction is roughly approximated by an expression of $\hbar\omega_a=86q_a^3$ at 150 K as indicated by dotted lines in Fig. 1. In contrast with usual ferromagnets, with increasing temperature the dispersion along the a^* direction is largely renormalized to higher spin-wave energy for the same q_a value in the measured q region and finally turns into the constant-E ridges above T_c[9] as shown in Figs. 1 and 2. On the other hand, along the b^* and c^* direction dispersions are renormalized a little with temperature.

Previously, precise measurements of magnetization performed by Takase *et al.*[8] revealed the anomalous temperature dependence of magnetization of MnP in the induced ferromagnetic phase under the external magnetic field along the c-axis. The temperature dependence of magnetization deviates from the $T^{3/2}$ law and it was approximated to be proportional to $T\ln T$ in a temperature range from 5 K to 140 K. In order to explain this unusual temperature dependence of magnetization they proposed a model of ferromagnetic spin-wave dispersion on the analogy with rare earth metals in which both ferromagnetic and helimagnetic state are realized. They assumed a flat dispersion in a smaller-q region and step-like increase in energy at $q=Q_h$ along the a-axis and $D_\perp q_\perp^2$ relation along the direction perpendicular to a-axis, that is,

$$\hbar\omega_q(T=0\mathrm{K})=D_\perp q_\perp^2+f(q_a)+\Delta,$$

$$f(q_a)=\begin{cases} 0 & 0\leqq q_a\leqq Q_h, \\ \infty & Q_h\leqq q_a, \end{cases}$$

where Δ is the energy gap at $q=0$. By fitting the calculated magnetization to the measured one, they obtained $D_\perp$ to be 39 meVÅ^2 at 0 K. Although parameters of their simple model-dispersions do not agree with the measured ones, the several features of this model correspond to those obtained by present measurements; flat dispersion at low-energy region and steeper increase in energy according to q^3 dependence of dispersion along the a^* direction and q^2 dependences along the b^* and c^* directions. Furthermore their two-magnon renormalization calculations using this model-dispersion represent the tendency of unusual renormalization along the a^* direction mentioned before. Anomalous initial decrease in magnetization would be due to the low-energy flat portion of dispersion which appear in the a^* direction.

Within a localized spin model, such an anomalous dispersion can be reproduced by assuming long-ranged exchange interactions. Actually our preliminary calculation of spin-waves using an isotropic Heisenberg model within a two-sublattice model suggests that the exchange interactions are very long-ranged, to be more precise, more than sixth-neighbour exchange interaction parameters are necessary in order to reproduce the measured spin-wave dispersions. Therefore proper account of the itinerant nature of d-electrons beyond a localized model is much more important for understanding the magnetism of MnP. The behaviour of spin-waves in the whole Brillouin zone as well as its damping is important information and further measurements of spin-waves at larger-q, ω region are in progress.

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