Detailed Studies on the Anomalous Hall Effect of Pyrochlore Molybdates

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Abstract

Neutron measurements and transport studies have been carried out on single crystals of the pyrochlore ferromagnet $Nd_2Mo_2O_7$, which has quite unusual Hall resistivity ρ_H. The magnetic structure has been determined at 1.6 K as a function of H, and based on this magnetic structure, the H-dependence of ρ_H is deduced by using the recently proposed chiral order mechanism. The results have turned out not to describe the observed behavior of ρ_H.

Key words: pyrochlore molybdate; anomalous Hall resistivity; spin chirality; neutron scattering

$Nd_2Mo_2O_7$ consists of individually formed networks of corner-sharing Mo_4- and Nd_4-tetrahedra and exhibits a ferromagnetic transition at temperature T_C=93 K, where the Mo-moments primarily order. The ordering of the Nd-moments becomes significant below $\sim$ 30 K. The low temperature(T) magnetic structure is non-collinear for both the Mo- and Nd-moments [1]. Unusual behavior of the Hall resistivity(ρ_H) of $Nd_2Mo_2O_7$ has been reported by the authors' group [2]: Above 30 K, the data of ρ_H is well described by $\rho_H = R_0H + 4\pi R_s M$ as for ordinary ferromagnets, where R_0 and R_s are the ordinary and anomalous Hall coefficients, respectively, and M is the total magnetization. However, below $\sim$ 30 K, the expression no more works and instead, another phenomenological expression $\rho_H = R_0H + 4\pi R_s M_{Mo} + 4\pi R_s' M_{Nd}$ ($R_s \cdot R_s' < 0$) has been found to describe the experimental results rather well, where M_{Mo} and M_{Nd}, and R_s and R_s' are the net magnetizations and the anomalous Hall coefficients corresponding to the Mo- and Nd-moments, respectively. The existence of the two components is supported by the studies of doping effects on the behavior of ρ_H [3]. R_s and R_s' are found not to exhibit significant decrease as T approaches zero in contrast to the case of ordinary ferromagnets. None of classical theories can describe these results consistently. A new proposal has been made that the ordering of the spin chirality χ which is locally defined as $\chi = \boldsymbol{S}_1 \cdot \boldsymbol{S}_2 \times \boldsymbol{S}_3$ for three spins $\boldsymbol{S}_j (j = 1 \sim 3)$ contributes to the Hall resistivity [4].

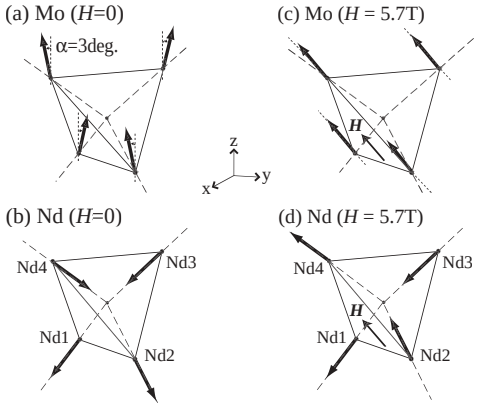

Fig. 1. Magnetic ordering patterns of Mo_4- and Nd_4-tetrahedra which can explain the observed intensities of the magnetic reflections at 1.6 K under the magnetic field at H= 0 and H = 5.7 T.

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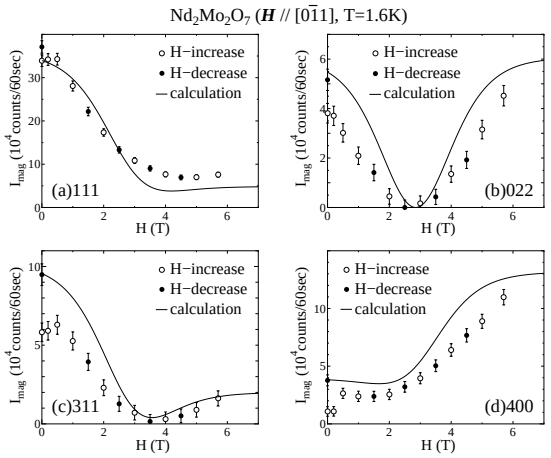

Fig. 2. Intensities of several magnetic reflections at 1.6 K are plotted against H, applied along [0$\bar{1}$1].

In the present work, neutron scattering studies in the applied magnetic field $\boldsymbol{H}(//[0\bar{1}1])$ up to 5.7 T have been carried out to clarify the relationship between the order of χ and the behavior of $\rho_{\rm H}$. The neutron measurements were carried out by using the triple axis spectrometer HQR(T1-1) installed at the thermal guide of JRR-3M of JAERI in Tokai, where double axis condition was adopted.

In the zero and finite magnetic field $H(//[0\bar{1}1])$, the neutron elastic scattering intensity has been measured on a single crystal of $Nd_2Mo_2O_7$ at various $\boldsymbol{Q}$-points at 113 K($> T_{\rm C}$) and 1.6 K($< T_{\rm C}$). The magnetic scattering intensity $I_{\rm mag}$ was obtained by taking the differences between the observed integrated intensities at two temperatures, where the absorption and extinction corrections were made, though the results of the analyses do not sensitively depend on the extinction corrections. The ordering patterns at 1.6 K, which can reproduce the intensities of the magnetic Bragg reflections at $H = 0$ are shown in Figs. 1(a) and 1(b). The Mo-moments align along the direction nearly parallel to the [001] or other equivalent axes, but have the slight tilting by the angle $\alpha = 3\ (\pm\ 3)^\circ$ towards the local principal axes, while the Nd-moments are along their principal axes with their net magnetization being antiparallel to that of the Mo-moments. The results indicate that there exists the relatively strong axial anisotropy at the Nd sites.

We have determined the magnetic structure at 1.6 K as a function of H, where the Mo-Mo and Mo-Nd exchange fields and the single ion anisotropies of the Mo- and Nd-moments are considered as the parameters and so chosen that they can reproduce the H-dependence of the observed magnetic scattering intensities, the examples of which are shown in Figs. 2(a)-2(d). The obtained ordering patterns at 1.6 K in the field $H = 5.7$ T are shown in Figs. 1(c) and 1(d). The Mo-moments

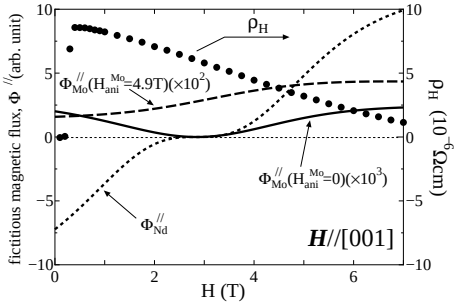

Fig. 3. Fictitious magnetic flux of the Mo- and Nd-moments along $\boldsymbol{H}(//[001])$, $\Phi^{\parallel}_{\rm Mo}$ and $\Phi^{\parallel}_{\rm Nd}$, respectively, is shown at 1.6 K against H. $\rho_{\rm H}$ is also shown by the closed circles.

align along the direction nearly parallel to $\boldsymbol{H}(//[0\bar{1}1])$ but they are tilted from the direction by the single ion anisotropy and the Mo-Nd exchange interaction. With increasing H up to 5.7 T, the Nd-moments at Nd2 and Nd4 sites turns their directions and their average magnitude also changes, while the magnitude and directions of the Nd-moments at Nd1 and Nd3 sites hardly change. We have also determined the magnetic structures under the conditions $\boldsymbol{H}//[001]$ and [111] by using the same parameters as used for $\boldsymbol{H}//[0\bar{1}1]$.

In the chiral order mechanism of $\rho_{\rm H}$, the spin chirality χ makes the fictitious magnetic flux of the Mo- and Nd-moments, $\boldsymbol{\Phi_{Mo}}$ and $\boldsymbol{\Phi_{Nd}}$, respectively. We calculate them at 1.6 K as a function of H by using the H-dependent magnetic structure. Their components parallel to $\boldsymbol{H}$, $\boldsymbol{\Phi^{\parallel}_{Mo}}$ and $\boldsymbol{\Phi^{\parallel}_{Nd}}$ is proportional to the anomalous Hall conductivity(, which is approximately considered to be proportional to the anomalous Hall resistivity here). They are shown in Fig. 3 for $\boldsymbol{H}//[001]$ for two effective magnetic fields, $H^{\rm Mo}_{\rm ani} = 4.9$ T and 0 introduced to consider the single ion anisotropy of the Mo-moments. The curves of $\boldsymbol{\Phi^{\parallel}_{Mo}}$ shown in Fig. 3 do not agree with the experimentally observed $\rho_{\rm H}$ [1] shown by the closed circles in Fig. 3. The observed curves of $\rho_{\rm H}$ cannot be described by the combinations of $\boldsymbol{\Phi^{\parallel}_{Mo}}$ and $\boldsymbol{\Phi^{\parallel}_{Nd}}$, either, though the anomalous Hall resistivity can basically be described, as stated above, by the sum of two components from $M_{\rm Mo}$ and $M_{\rm Nd}$ These results indicate that the chiral order mechanism alone does not describe the behavior of $\rho_{\rm H}$ of the present system.

References

[1] Y. Yasui, Y. Kondo, M. Kanada, M. Ito, H. Harashina, M. Sato and K. Kakurai, J. Phys. Soc. Jpn. **70** (2001) 284.

[2] S. Yoshii, S. Iikubo, T. Kageyama, K. Oda, Y. Kondo, K. Murata and M. Sato, J. Phys. Soc. Jpn. **69** (2000) 3777.

[3] T. Kageyama, S. Iikubo, S. Yoshii, Y. Kondo, M. Sato and Y. Iye, J. Phys. Soc. Jpn. **70** (2001) 3006.

[4] K. Ohgushi, S. Murakami and N. Nagaosa, Phys. Rev. B **62** (2000) R6065.