Spin-chirality induced anomalous Hall effect in pyrochlore ferromagnets

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When an electron hops between atoms in solids under magnetic field $\vec{B}$, the quantum mechanical amplitude obtains a complex factor with its phase determined by the vector potential $\vec{A}$ corresponding to $\vec{B}$ ($= \nabla \times \vec{A}$). In metallic magnets, the analogous complex factor occurs when an electron hops along the non-coplanar spin configurations, and the effective magnetic field is represented by the spin chirality, namely the solid angle subtended by the spins. This internal effective magnetic field is expected to manifest itself in the anomalous Hall effect[1-3]. The transverse resistivity ρ_{H} in ferromagnets consists of the two contributions, i.e.,

$$\rho_{\mathrm{H}} = R_{\mathrm{o}}B + 4\pi R_{\mathrm{s}}M, \tag{1}$$

where B, M, R_{o}, R_{s}, are magnetic induction, magnetization, ordinary Hall coefficient, and anomalous Hall coefficient, respectively. The second term, which is proportional to the magnetization, represents the anomalous Hall effect. Conventionally, the anomalous Hall effect has been ascribed to spin-orbit interaction and the spin-polarization of conduction electrons[4], which result in the asymmetry in terms of orbital angular momentum, or to the asymmetric skew scattering of conduction electrons by the fluctuation of localized moments[5]. These theories assume the collinear spin structure. Recently, however, the relevance of the non-coplanar spin configuration to the anomalous Hall effect has been discussed in the context of perovskite-type manganites at high temperatures[1].

In manganites or related double-exchange ferromagnets, due to the strong Hund's-rule coupling between the e_g conduction electrons and the localized t_{2g} spins, the transfer integral from site i to j is given[6] by

$$t_{ij} = t[\cos(\theta_i/2)\cos(\theta_j/2) + \sin(\theta_i/2)\sin(\theta_j/2)e^{i(\phi_i - \phi_j)}], \tag{2}$$

where θ_i and ϕ_i are the polar coordinates of the spin direction. This transfer integral is a complex number, and could produce the gauge flux. When we consider an electron hopping along a loop $1 \to 2 \to 3 \to 1$, the total phase acquired by the electron turns out to be the solid angle subtended by the three spins , and to be proportional to the spin chirality $\vec{S}_1 \cdot \vec{S}_2 \times \vec{S}_3$. Such a gauge flux acts as a fictitious magnetic field $\vec{b}$ and affects the charge dynamics in the same way as a real magnetic field does. At finite tempearatures, the spin configuration is disordered by thermal agitation and the topological excitations are activated to produce the finite spin chirality, which contributes to the transverse conductivity. However, it is rather difficult to specify uniquely the mechanism of anomalous Hall effect at finite temperature. In fact, the anomalous Hall term vanishes at low temperatures in the manganites, much as it does in conventional ferromagnets, and the temperature dependence may not be contradictory, at least qualitatively, to the existing theories[4,5]. At zero temperature, the periodicity of the crystal enforces the uniform component of the gauge flux to vanish. As discussed recently[2], the geometrical and topological properties of the lattice are crucial for the Berry phase mechanism of anomalous Hall effect at $T = 0$ K, and Kagome- and pyrochlore-lattice are two of the rare structures which satisfy this condition.

In this talk, we present recent experimental evidence[7-9] that the anomalous Hall effect in pyrochlore-type molybdate does arise from this spin chirality mechanism. The pyrochlore ($A_2B_2\mathrm{O}_7$) lattice is composed of two sublattices of A-site and B-site, which are structurally identical but are displaced by half a lattice constant from each other. In each sublattice, the ions form infinite network of corner-sharing tetrahedra. In the case of $B=$ Mo, the system shows a transition from spin-glass insulator to ferromagnetic metal with the change of A-site ion (rare-earth species). A typical ferromagnetic metal, $\mathrm{Nd_2Mo_2O_7}$, has a Curie temperature of about 90 K, and shows anomalous Hall effect below the Curie temperature. What is unique to this compound is that the anomalous Hall term, or the Hall conductivity derived from the Hall resisitivity, never ceases to increase all the way down to 2 K. Furthermore, the Hall conductivity shows clear anisotropy below the temperature where Nd moment begins to grow rapidly. This behavior is in sharp contrast with many ferromagents and with prediction by conventional theories, but is naturally accounted for in terms of the Berry phase theory.

One of the important predictions by the Berry phase theory is that the sign of ρ_{H} changes when a strong magnetic field is applied along [111] direction, whereas it does not when the field is applied along [100] or [110] direction. To test this prediction, we have measured the anisotropic Hall effect and magnetizaiton for the field up to 27 T and temperature down to 50 mK. The magnetization curve shows little temperature dependence below 2 K and the values of saturation moments are in accord with the assumption that the Nd moment is of Ising-anisotropy with the magnitude and Ising axis being $\approx 2.3\mu_B$ and $\langle 111 \rangle$ direction, respectively. The ρ_{H} changes sign when the field is applied along [111] direction, but does not when applied along [100] or [110] direction. This fact is consistent with the prediction by the Berry phase theory, evidencing the spin-chirality mechanism of anomalous Hall effect for $\mathrm{Nd_2Mo_2O_7}$.

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