Intrinsic Hall Effects in Transition Metals

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We investigate the intrinsic spin Hall conductivity (SHC) in metallic d-electron systems, by focusing on the Sr_2MO_4 (M=Ru,Rh,Mo) [1] and $4d$ and $5d$ transition metals [2,3]. The obtained SHCs are about 10^4 times larger than the value in n-type semiconductors. We find that a conduction electron acquires a Berry phase due to the complex d-orbital wavefunction, in the presence of the spin orbit interaction. This orbital-derived Berry phase (orbital Aharonov-Bohm effect) is the origin of giant SHC in d-electron systems. In transition metals, we find that the SHC is proportional to the spin-orbit polarization at the Fermi level, which is positive (negative) in metals with more than (less than) half-filling. We also derive a general expression for the SHC in the superconducting state, and find that a prominent SHC below T_c can emerge via current vertex correction [4].

Next, we propose a new mechanism of spin structure-driven anomalous Hall effect (AHE) by taking account of the d-orbital degree of freedom [5]. We find that the Berry phase due to orbital AB effect is strongly enhanced by the non-collinear spin structure, and thus the AHE driven by this orbital-derived Berry phase is much larger than the AHE induced by spin chirality, and it naturally explains the salient features of spin structure-driven AHE in pyrochlore $Nd_2Mo_2O_7$. Since the proposed AHE can occur even for coplanar spin orders ($M_z = 0$), it is expected to emerge in other interesting geometrically frustrated systems.

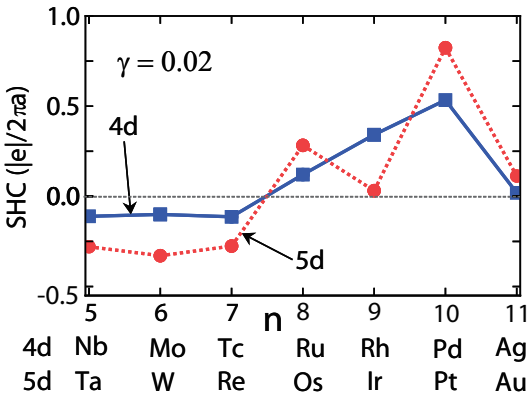

Figure 1: Obtained SHCs for $4d$ and $5d$ transition metals based on the nine-orbital model [2].

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[2] T. Tanaka, H. Kontani, M. Naito, T. Naito, D. S. Hirashima, K. Yamada, and J. Inoue, Phys. Rev. B **77**, 165117 (2008).

[3] H. Kontani, T. Tanaka, D. S. Hirashima, K. Yamada, and J. Inoue, Phys. Rev. Lett. **102**, 016601 (2009).

[4] H. Kontani, J. Goryo, and D.S. Hirashima, Phys. Rev. Lett. **102**, 086602 (2009).

[5] T. Tomizawa and H. Kontani, arXiv:0901.2774.