[Japanese/English]

Unified theory of anomalous Hall effect, anomalous Nernst-Ettingshausen effect, and anomalous thermal Hall effect in ferromagnets

— intrinsic Berry-phase mechanism versus extrinsic mechanisms —

Novel crossovers found in the quantum (T=0) anomalous Hall transport by means of the gauge-covariant Keldysh formalism

I. Extrinsic regime in the superclean metal, where the skew-scattering (Mott-scattering) dominates over the intrinsic contribution: $\sigma_{xy} \propto \sigma_{xx}$

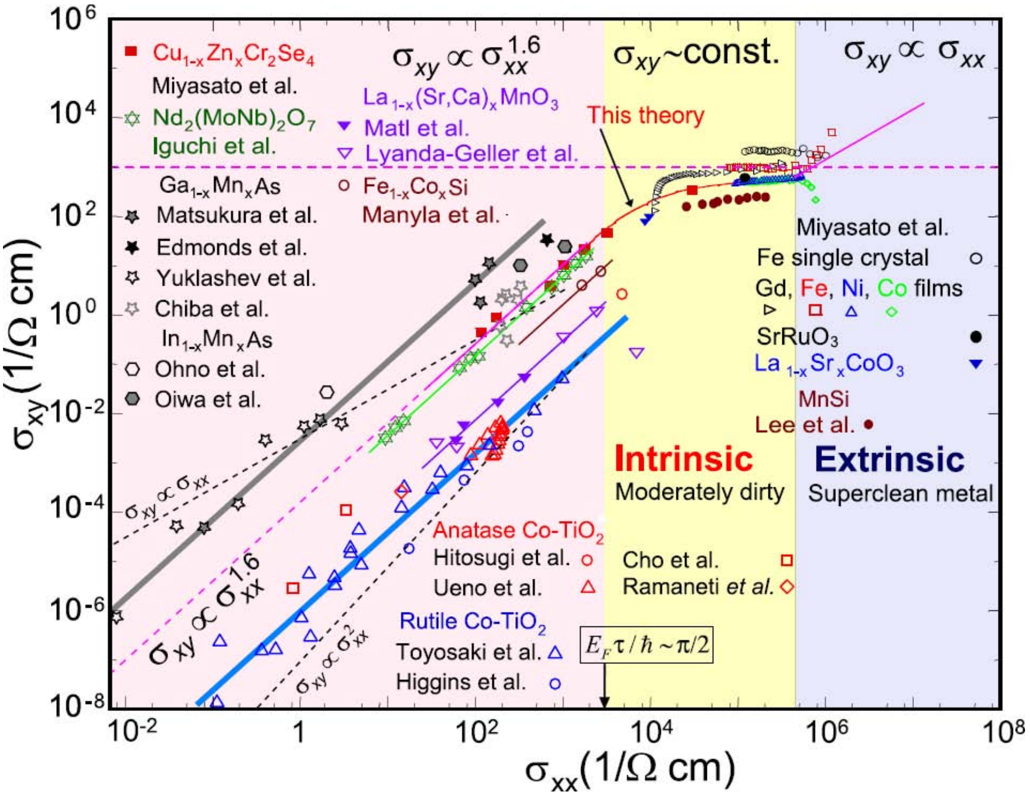
II. Intrinsic regime in the moderately dirty metal: $\sigma_{xy} \propto const.$

Berry-phase contribution resonantly enhanced by the avoided-crossing of band dispersions across the Fermi level.

III. Dephased intrinsic regime in the dirty metal: $\sigma_{xy} \propto \sigma_{xx}^{1.6}$

It is important that the $\sigma_{xy} \propto \sigma_{xx}^{1.6}$ behavior requires a dephasing of the Berry phase, but not necessarily the Anderson localization in 3D or

the weak localization in 2D which lead to rather different behaviors [5,6].



References:

1. For the first report on the two crossovers and the associated scaling behaviors, see *Shigeki Onoda*, Naoyuki Sugimoto, and Naoto Nagaosa, "Intrinsic vs. extrinsic anomalous Hall effect in ferromagnets": Physical Review Letters **97**, 126602 (2006).
2. For the self-contained and comprehensive report on the unified theory of anomalous Hall effect as well as its application to the anomalous Nernst-Ettingshausen and Leduc-Rhigi effects, see *Shigeki Onoda*, Naoyuki Sugimoto, and Naoto Nagaosa, "Quantum transport theory of anomalous electric, thermoelectric, and thermal Hall effects in ferromagnets": Physical Review B **77**, 165103 (2008). Selected as an Editors' suggestion. The above summary of experimental data and the relevant references also included.
3. For the *gauge-covariant* reformulation of the nonequilibrium Keldysh Green's function in *multi-band* systems and its application to linear transport coefficients, see *Shigeki Onoda*, Naoyuki Sugimoto, and Naoto Nagaosa, "Theoy of Non-Equilibirum States Driven by Constant Electromagnetic Fields:

Non-Commutative Quantum Mechanics in the Keldysh Formalism": Progress of Theoretical Physics **116**, 61 (2006).

4. The first experimental verification of the crossovers and the scaling behaviors has been reported by T. Miyasato, N. Abe, T. Fujii, A. Asamitsu, *S. Onoda*, Y. Onose, N. Nagaosa, and Y. Tokura, "Universal scaling behavior of anomalous Hall effect and anomalous Nernst effect in itinerant ferromagnets": Physical Review Letters **99**, 086602 (2007).
5. Weak-localization corrections to the anomalous Hall conductivity have been calculated by, for instance, V.K. Dugaev, P. Bruno, and J. Barnas, Physical Review B **64**, 144423 (2001) and P. Mitra, R. Misra, A.F. Hebard, K.A. Muttalib, and P. Wölfle, Physical Review Letters **99**, 046804 (2007).
6. The phonon-assisted anomalous Hall conductivity in the localized regime has been calculated by A. A. Burkov and L. Balents, Physical Review Letters **91**, 057202 (2003).

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