Nonequilibrium Phenomena in Quantum Spintronics

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Electronics has a long research history and has explored information processing, conduction, and transport phenomena by making use of electric charge and current. Spintronics [1] is a large sub field of electronics, in which spin (angular momentum) degrees of freedom are efficiently utilized in addition to charge degrees of freedom. It began in late 20th century and had originally developed from the perspective of application. On the other hand, in the last decades, the fundamental scientific research in spintronics has progressed as well. Furthermore, the connections between spintronics and related fields have significantly grown up: For instance, many studies of magnetism [2], multiferroics [3] and topological electron systems [4] are strongly associated with spintronics.

In this winter school, I would like to review some introductory topics of spintronics from a perspective of statistical and condensed-matter physics. Spintronics offers a nice platform of nonequilibrium phenomena and nonequilibrium physics [5,6]. In such nonequilibrium properties, one important concept is spin current [1], the flow of (spin) angular momentum. I will mainly review the nonequilibrium physics related to spin current.

I would like to divide my lecture into three parts. (i) In the first part, I will explain important concepts and phenomena in modern spintronics, including spin current, spin Hall effect, inverse spin Hall effect, spin Seebeck effect, spin pumping, etc. (ii) Secondly, I will review representative magnetic states studied in spintronics and magnetism, such as magnetically ordered states, noncollinear spin states with topological spin textures [2,3,7], and quantum spin liquids [8]. Then I will shortly review the mathematical foundations describing these magnetic states, which includes the spin-wave theory [2], low-energy field theory approaches [8], the bosonization [9], etc. (iii) Finally, as a typical nonequilibrium phenomenon in spintronics, I will focus on the spin Seebeck effect (SSE) [10], where spin current is generated by temperature gradient. I discuss how we can understand SSE from the microscopic view with Green's function techniques [6].

I think that the audience can relatively easily understand the contents of (i) and (ii), whereas the third part (iii) might be difficult, especially, for undergraduate students to deeply understand. However, I will try to give pedagogical contents for broad audiences, showing appropriately nice textbooks and reviews such as Refs. [1]-[10].

[1] For example, see *Spin Current* edited by S. Maekawa, *et al.* (Oxford Univ, 2007).

[2] For example, see R. M. White, *Quantum Theory of Magnetism* (Springer, 2007); D. C. Mattis, *Theory of Magnetism* (World Scientific, 2006); K. Yoshida, *Theory of Magnetism* (Springer, 1998).

[3] For example, see Y. Tokura, S. Seki and N. Nagaosa, Rep. Prog. Phys. **77**, 076501 (2014).

[4] For example, see S.-Q. Shen, *Topological Insulators* (Springer, 2012); B. A. Bernevig, *Topological Insulators and Topological Superconductors* (Princton Univ, 2013); D. Vanderbilt, *Berry Phases in Electronic Structure Theory* (Cambridge Univ, 2018).

[5] H.-P. Breuer and F. Petruccione, *The Theory of Open Quantum Systems* (Oxford Univ, 2007).

[6] G. Stefanucci and R. v. Leeuwen, *Nonequilibrium Many-Body Theory of Quantum Systems* (Cambridge Univ, 2013); H. J. W. Haug and A.-P. Jauho, *Quantum Kinetics in Transport and Optics of Semiconductors* (Springer, 2007); A. M. Zagoskin, *Quantum Theory of Many-Body Systems* (Springer, 2014).

[7] S. Seki and M. Mochizuki, *Skyrmions in Magnetic Materials* (Springer, 2016)

[8] L. Balents, Nature **464**, 199 (2010); L. Savary and L. Balents, Rep. Prog. Phys. **80**, 016502 (2017); X.-G. Wen, *Quantum Field Theory of Many-Body Systems* (Oxford Univ, 2007); Y. Motome and J. Nasu, J. Phys. Soc. Jpn. **89**, 012002 (2020).

[9] T. Giamarchi, *Quantum Physics in One Dimension* (Oxford Univ, 2003); P. Francesco, P. Mathieu and D. Senechal, *Conformal Field Theory* (Springer, 1997).

[10] T. Uchida, *et al*, App. Phys. Lett. **97**, 172505 (2010); H. Adachi, *et al*, Phys. Rev. B **83**, 094410 (2011); D. Hirobe, *et al*, Nature Phys. **13**, 30 (2017); K. Masuda and M. Sato, arXiv:2310.03271; T. Kikkawa and E. Saitoh, Ann. Rev. Cond. Mat. Phys. **14**, 129 (2023).