磁化構造中の伝導電子の理論

多々良源
(理化学研究所創発物性科学研究センター (CEMS))

Theory of electron transport in the presence of magnetization textures

G. Tatara
RIKEN Center for Emergent Matter Science (CEMS)

1 Introduction

In this paper, we discuss two topics, an emergent electromagnetic field which couples to electron's spin in ferromagnetic metals [1] and current-induced torques [2] from the theoretical viewpoints.

Our technology is based on various electromagnetic phenomena. For designing electronics devices, thus, the Maxwell's equation is of essential importance. The mathematical structure of the electromagnetic field is governed by a U(1) gauge symmetry, i.e., an invariance of physical laws under phase transformations. The gauge symmetry is equivalent to the conservation of the electric charge, and was established when a symmetry breaking of unified force occured immediately after the big bang. The beautiful mathematical structure of charge electromagnetism was therefore determined when our universe started, and there is no way to modify its laws.

Fortunately, charge electromagnetism is not the only electromagnetism allowed in the nature. In fact, electromagnetism arises whenever there is a U(1) gauge symmetry associated with conservation of some effective charge. In solids, there are several systems which have the U(1) gauge symmetry as a good approximation. Solids could thus display several types of effective electromagnetic fields. A typical example is a ferromagnetic metal. In ferromagnetic metals, conduction electron spin (mostly s electron) is coupled to the magnetization (or localized spins of d electrons) by an interaction called the sd interaction, which tends to align the electron spin parallel (or anti-parallel) to the localized spin. This interaction is strong in most $3d$ ferromagnetic metals, and as a result, conduction electron's spin originally consisting of three components, reduces to a single component along the localized spin direction. The remaining component is invariant under a phase transformation, i.e., has a U(1) gauge symmetry just like the electric charge does. A spin electromagnetic field thus emerges that couples to conduction electron's spin. The first subject of the present paper is this spin electromagnetic field. The world of spin electromagnetic field is richer than that of electric charge, since the electron's spin in solids is under influence of various interactions such as spin-orbit interaction. We will in fact show that magnetic monopole emerges from spin relaxation processes. Spin electromagnetic field drives electron's spin, and thus plays an essential role in spintronics. The other subject, the current-induced torques, is a reciprocal effect of spin electromagnetic field.

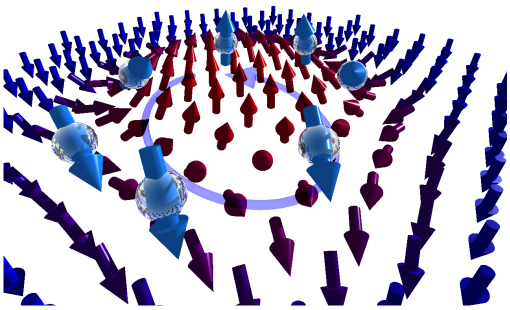

Fig. 1 The spin of a conduction electron is rotated by a strong sd interaction with magnetization as it moves in the presence of a magnetization texture, resulting in a Berry's phase factor $e^{i\varphi}$

The effect of spin electromagnetic field was partially discussed already in 1986 by Berger, who discussed a voltage generated by a canting of wall plane of a driven domain wall [3]. Emergence of effective electromagnetism coupling to electron's spin was pointed out by use of gauge field argument by Volovik in 1987 (Ref. [4]). Stern discussed the motive force in the context of the spin Berry's phase, and discussed similarity to the Faraday's law [5]. Spin motive force was rederived in Ref. [6] in the case of domain wall motion. It was argued in the context of topological pumping in Ref. [7]. Duine discussed spin electric field including the effect of spin relaxation by use of non-adiabaticity parameter (β) [8,9]. The Hall current induced by a spin electric field in the presence of spin-orbit interaction was theoretically studied by Shibata and Kohno [10,11]. The effect of Rashba interaction on spin electric field was discussed in Refs. [12,13]. These works [6,8,10,12,13] have focused solely on the spin electric field. The magnetic component of Rashba-induced spin electromagnetic was discussed in Ref. [14].

2 Emergence of spin gauge field

Let us here demonstrate that a spin gauge field emerges from a strong *sd* exchange interaction (adiabatic limit). Because of the *sd* interaction, spin of electron traveling through a magnetization structure follows the local spin and rotates with it (Fig. 1), and the spin acquires a geometric phase [15]. The phase is written as an integral of an effective gauge field, $\boldsymbol{A}_{\rm s}$, along its path C as $\varphi = \frac{e}{\hbar}\int_C d\boldsymbol{r}\cdot\boldsymbol{A}_{\rm s}$, where e is electron charge and $\hbar$ is the Planck's constant devided by 2π. The vector $\boldsymbol{A}_{\rm s}$ turns out to be

$$\boldsymbol{A}_{\rm s} = \frac{\hbar}{2e}(1-\cos\theta)\nabla\phi. \tag{1}$$

Existence of the phase means that there is an effective magnetic field, $\boldsymbol{B}_{\rm s}$, as seen by rewriting the integral over a closed path using the Stokes theorem $\varphi = \frac{e}{\hbar}\int_S d\boldsymbol{S}\cdot\boldsymbol{B}_{\rm s}$, where $\boldsymbol{B}_{\rm s} \equiv \nabla\times\boldsymbol{A}_{\rm s}$ represents curvature. This phase φ attached to electron spin is called the spin Berry's phase. Time-derivative of phase is equivalent to a voltage, and thus we have effective electric field defined by $\dot{\varphi} = -\frac{e}{\hbar}\int_C d\boldsymbol{r}\cdot\boldsymbol{E}_{\rm s}$, where $\boldsymbol{E}_{\rm s} \equiv -\dot{\boldsymbol{A}}_{\rm s}$. $\boldsymbol{E}_{\rm s}$ and $\boldsymbol{B}_{\rm s}$ are called spin electric and magnetic field, respectively. They satisfy the Faraday's law,

$$\nabla\times\boldsymbol{E}_{\rm s} + \dot{\boldsymbol{B}}_{\rm s} = 0, \tag{2}$$

as a trivial result of their definitions. The fields have a structure of electromagnetism and thus a spin electromagnetic field coupled to electron's spin emerges. One should note that those fields are real or observable ones coupling to real electric charge and current and not just 'fictitious fields'.

In the presentation, phenomena arising from the spin gauge field, Eq. (1), are discussed.

References

1) G. Tatara and N. Nakabayashi. Emergent spin electromagnetism induced by magnetization textures in the presence of spin-orbit interaction (invited). *Journal of Applied Physics*, Vol. 115, No. 17, p. 172609, 2014.

2) G. Tatara, H. Kohno, and J. Shibata. Microscopic approach to current-driven domain wall dynamics. *Physics Reports*, Vol. 468, pp. 213–301, 2008.

3) L. Berger. Possible existence of a josephson effect in ferromagnets. *Phys. Rev. B*, Vol. 33, No. 3, pp. 1572–1578, 1986.

4) G. E. Volovik. Linear momentum in ferromagnets. *J. Phys. C: Solid State Phys.*, Vol. 20, pp. L83–L87, 1987.

5) A. Stern. Berry's phase, motive forces, and mesoscopic conductivity. *Phys. Rev. Lett.*, Vol. 68, No. 7, pp. 1022–1025, Feb 1992.

6) S. E. Barnes and S. Maekawa. Generalization of faraday's law to include nonconservative spin forces. *Phys. Rev. Lett.*, Vol. 98, No. 24, p. 246601, 2007.

7) S. A. Yang, G. S. D. Beach, C. Knutson, D. Xiao, Z. Zhang, M. Tsoi, Q. Niu, A. H. MacDonald, and J. L. Erskine. Topological electromotive force from domain-wall dynamics in a ferromagnet. *Phys. Rev. B*, Vol. 82, p. 054410, Aug 2010.

8) R. A. Duine. Spin pumping by a field-driven domain wall. *Phys. Rev. B*, Vol. 77, No. 1, p. 014409, 2008.

9) M. E. Lucassen, G. C. F. L. Kruis, R. Lavrijsen, H. J. M. Swagten, B. Koopmans, and R. A. Duine. Spin motive forces due to magnetic vortices and domain walls. *Phys. Rev. B*, Vol. 84, p. 014414, Jul 2011.

10) J. Shibata and H. Kohno. Inverse spin hall effect driven by spin motive force. *Phys. Rev. Lett.*, Vol. 102, No. 8, p. 086603, 2009.

11) J. Shibata and H. Kohno. Spin and charge transport induced by gauge fields in a ferromagnet. *Phys. Rev. B*, Vol. 84, p. 184408, Nov 2011.

12) K.-W. Kim, J.-H. Moon, K.-J. Lee, and H.-W. Lee. Prediction of giant spin motive force due to rashba spin-orbit coupling. *Phys. Rev. Lett.*, Vol. 108, p. 217202, May 2012.

13) G. Tatara, N. Nakabayashi, and K.-J. Lee. Spin motive force induced by rashba interaction in the strong *sd* coupling regime. *Phys. Rev. B*, Vol. 87, p. 054403, Feb 2013.

14) N. Nakabayashi and G. Tatara. Rashba-induced spin electromagnetic fields in the strong sd coupling regime. *New Journal of Physics*, Vol. 16, No. 1, p. 015016, 2014.

15) J. J. Sakurai. *Modern Quantum Mechanics*. Addison Wesley, 1994.