【Grant-in-Aid for Scientific Research (S)】

Emergent electromagnetic induction in magnetic conductors

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Purpose and Background of the Research

●Outline of the Research

Faraday's law of electromagnetic induction forms the foundation of modern civilization, from generators and motors to inductor elements. In magnetic solids, a virtual (emergent) magnetic field and a virtual (emergent) electric field obey a generalized Faraday law in the nano-scale world. We will aim to downsize conventional inductor elements one million times, exploring the response of magnetic spins to time-varying electromagnetic fields for a group of materials where localized spins and conduction electrons are strongly coupled.

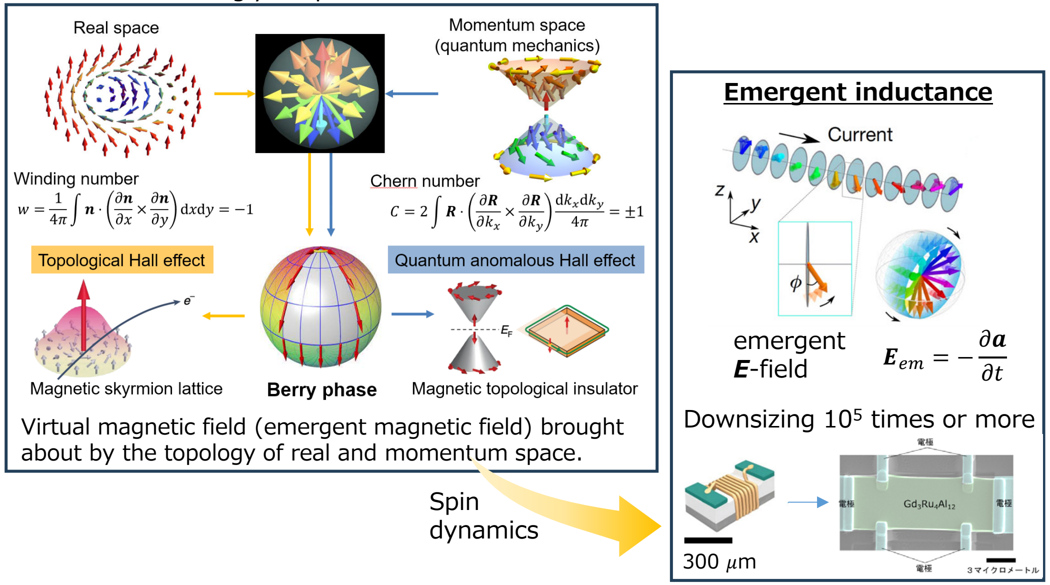

Figure 1. Exploration of emergent electromagnetic induction in magnetic materials

●Research background

In the field of quantum technology, a key challenge is to bring together two seemingly disparate research trends: "Quantum Matter", where strong Coulomb interactions between electrons produce ordering of charge and spin, based on the deep principles of quantum mechanics; and "emergent electromagnetism" (or topology), which started with the pioneering quantum Hall effect in semiconductor physics and which explains the appearance of virtual (emergent) electromagnetic fields in solids. A phenomenon at the interface of these two research trends is emergent electromagnetic induction, i.e., the appearance of an emergent electric field originating from the time variation of the emergent magnetic field (Fig. 1). This research enables search for new alternatives to micro-scale devices, and is considered significant for the future of quantum technology.

●Purpose of research

In strongly correlated electron systems, localized magnetism and conduction electrons are coupled and can drive emergent electromagnetic induction (EEI) phenomena. Using helimagnets, multiferroic conductors, and polar magnetic semimetals, we will establish a unified theoretical framework for EEI. This new understanding will be applied to the design of new nano- and micrometer-sized devices from quantum materials, which can replace coils and other circuit elements based on classical electromagnetic induction. As such, our research enables device miniaturization and future power-saving technology.

Expected Research Achievements

We consider design strategies for emergent induction (EEI) in conductors, using: (a) helimagnets, (b) generalized multiferroics, and (c) magnetic skyrmion hosts.

●Helimagnetic conductors

In helimagnets with a chiral 'twist' of magnetic spins, an applied AC current creates a noncollinear spin configuration that oscillates in time, resulting in an emergent electric field (Fig. 2). The principal investigator demonstrated a complex impedance in helimagnets, with imaginary part proportional to the frequency of the applied current; thus mimicking the voltage induced in a classical coil (inductor) by an applied current.

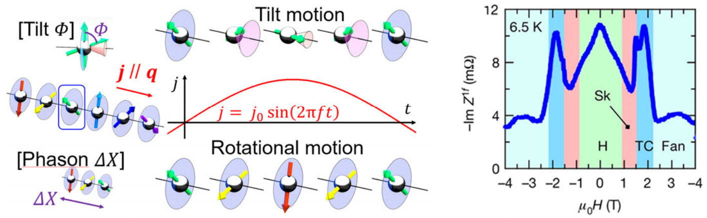

Fig. 2: Mechanism of emergent inductance from tilting and phason degrees of freedom in in a spin-helix structure, and imaginary part of complex impedance (inductance) observed in $Gd_3Ru_4Al_{12}$.

A commercial micro-inductor coil has a volume ≤ 1 mm^3, but a helimagnetic device roughly one million time smaller exhibits a similar, or higher, inductance. Yet, our understanding of the underlying physics remains incomplete.

●Generalized multiferroic conductors

Multiferroic insulators host magneto-electric (ME) effects which enable the control of a magnetization (polarization) by an applied electric (magnetic) field. In generalized multiferroics, space and time inversion symmetries are both broken by magnetic order. Here, the conducting version of the ME effect is EEI, where time-dependent magnetization creates electric currents and vice versa. For example, in Rashba semiconductors, a rotating magnetic field induces oscillating electric fields through EEI.

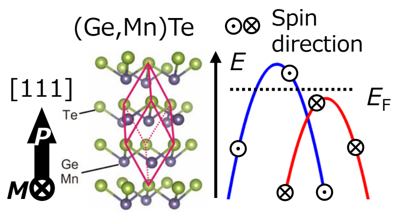

Fig. 3: Rashba semiconductor, an example of a multiferroic conductor.

●Magnetic skyrmion

Above, we focused on emergent electric fields E_{em} generated by current or magnetic field drive, even in absence of a static emergent magnetic field B_{em}. Magnetic skyrmion vortices realize static B_{em}; its uniform motion induces E_{em}. We will detect the dynamic deformation of a skyrmion lattice by strong oscillating currents in micro-devices, sensing E_{em} perpendicular to the direction of skyrmion motion.

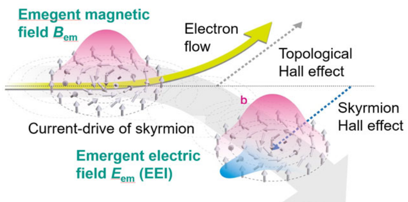

Fig. 4: Current induced skyrmion motion and emergent electric field E_{em}.

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