Research Group for Spin-Energy Transformation Science

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Spin is the angular momentum and the source of magnetization. Its rotational motion is limited in one direction under a magnetic field. Our strategy is to utilize this special nature of spin to enhance energy efficiency, which is the key for sustainability of our society. Spin Seebeck effect, spin motive force, rectification of heat flow are our main targets. In addition, the special nature of spin leads to a new principle to control mechanical rotation and vibration. In this fiscal year, the Barnet effect has been studied in several rear-earth metals [1]. This subject is explained in Research Highlights. Other two interesting results are stated below.

Spin Seebeck Effect by Spinon Spin Current

Spin Seebeck effect is observed as thermoelectric generation using a device of metal and magnet films. So far various ferromagnets have been examined as the magnetic films. Temperature gradient applied to the device produces magnetically polarized current (spin current) in the ferromagnet. The spin current is injected into the metallic film and is converted into the charge current by the inverse spin Hall effect. In a usual insulating ferromagnet, the spin current is carried by magnons. On the other hand, low-dimensional quantum spin systems do not show long-ranged order and their magnetic excitations are described by spinons, which are topological excitations in the spin liquid state, i.e., highly fluctuating state of spins. What is the difference between magnons and spinons? We successfully observe the spin Seebeck effect by the spinons using the device of Pt and Sr_2CuO_3. Figure 1 (a) shows schematic figure of quantum spin chain composed of spin-1/2, which is localized on Cu surrounded by four oxygens. Figure 1 (b) shows our device geometry. The injected spin current I_s in Pt is converted to the charge current and leads to voltage V perpendicular to I_s. As expected, V is observed only when a temperature gradient ∇T is parallel to the spin chain as shown in Fig. 1 (c). This is the evidence of spinon spin Seebeck effect. In particular, V is enhanced around 20 K, where the spinon picture works well. Surprisingly the sign of voltage is negative and is opposite to the spin Seebeck effect using usual ferromagnet. The sign difference is attributed to a symmetry of spinon band.

Spin Current in a Half-metallic Ferromagnet

Another way to generate a spin current is injection of a charge current into a ferromagnetic metal, in which the charge current is magnetically polarized. However, the charge current is always accompanied by the Joule heating. Hence, the spin current without charge current is called pure spin current and is expected to be a potential candidate as spin injector of magnetic memories. In this case, the key is the polarization of ferromagnetic metal defined by the ratio of $n_\uparrow - n_\downarrow$ and $n_\uparrow + n_\downarrow$ with densities of up-spin $n_\uparrow$ and down-spin $n_\downarrow$. Idealistically, $n_\uparrow=1$ and $n_\downarrow=0$ or vice versa is the best to effectively generate the spin current. This is called half-metallic ferromagnet (HMF) as shown in Fig. 2 (a), in which the up-spin band is metallic and the down-spin band is insulating. However, the pure spin current is impossible in Fig. 2 (a), since the pure spin current is composed of angular momentum 1. Here, we remember that the HFM is ferromagnet and has the Goldstone-mode associated with the spinwave. This spin fluctuation must exist in the HFM and leads to the smeared gap as shown in Fig. 2 (b). This is apparently the correlation effect of electrons in the HFM. We study the spin Hall effect in the HFM using Kubo formula assuming some extrinsic mechanism called side-jump and skew scatterings. It is found that the spin Hall conductivity (SHC) is proportional to $T^{2/3}$. This SHC sensitive to a temperature T can be a tool to study the minority-spin state, which is rather difficult to detect by other methods.

References

[1] Y. Ogata et al., Appl. Phys. Lett. **110**, 072409 (2017).
[2] D. Hirobe et al., Nature Physics **13**, 30–34 (2017).
[3] Y. Ohnuma et al., Phys. Rev. B **94**, 184405 (2016).

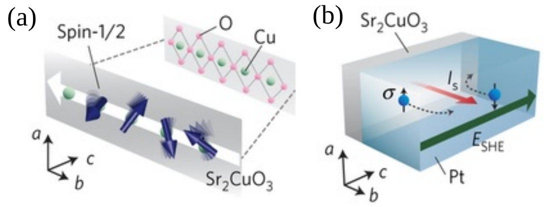
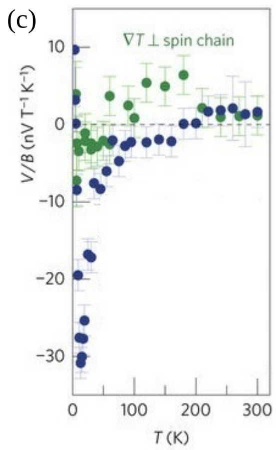


Fig.1 (a) Schematic figure of spin chain in Sr_2CuO_3. (b) Schematic figure of longitudinal spin Seebeck device. By the inverse spin Hall effect, the spin current I_s generated by a temperature gradient is converted to the electric field $E_{SHE} \propto \sigma \times I_s$. (c) Observed voltage V divided by magnitude of magnetic field B for temperature gradient ∇T parallel (blue) and perpendicular (green) to the spin chain.



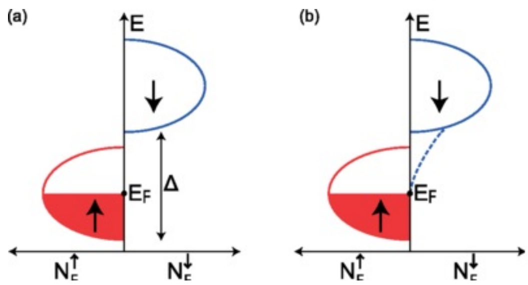


Fig.2 Schematic figures of density of states in a half-metallic ferromagnet; (a) without spin fluctuations and (b) with spin fluctuations [3].