Study on a factor of spin current power generation by neutron scattering

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Spin current is a flow of spin-angular momentum. The spin current power generation bases on a revolutionary method that can generate electricity in an insulator from the flow of the spin current produced by, for example, a temperature gradient. In other words, the spin current is a flow of magnon. The flow results in a voltage on the electrodes of platinum via the inverse spin Hall effect [1]. The power generation has been investigated using ferromagnetic materials such as yttrium iron garnet (YIG) with high efficiency [2]. The composition of the magnetic material YIG is $Y_3Fe_5O_{12}$ with up and down Fe^{3+} spins, which are in a ratio of 3 : 2, as shown in Fig. 1. It results in a ferrimagnetic state. The rotation of these two types of spins is not free in three dimensions and spins can only rotate in an anticlockwise direction at low energies as shown in Fig. 1. Such restrictions come from the crystallographic symmetry of spins. Furthermore, it was theoretically pointed out that this rotation is closely related to the spin current of YIG, and if both clockwise and anticlockwise rotations are mixed, the efficiency decreases [3]. In this YIG, it turns out that these two types of rotational energies are split by about 30 meV, therefore, only the anticlockwise rotation in Fig. 1 occurs at low temperatures. Furthermore, the magnitude of the spin current depends on the state number of spin rotations (magnon) which determines the spin current power generation efficiency. The state number of the magnon can be measured as the magnon density of states (MDOS) by inelastic neutron scattering (INS). However, it has been experimentally difficult because it is necessary to evaluate the scattering intensity in an absolute scale, therefore, it has not been directly determined even in a popular magnet YIG so far.

The MDOS on YIG has been studied [4] as shown in Fig. 2 by INS in a wide energy range over three orders of magnitude using three INS spectrometers, 4SEASONS, AMATERAS, and DNA in the Material and Life Science Experimental Facility of J-PARC Center. With this knowledge to derive the MDOS of a complicated magnetic structure like YIG, we can now apply this method to many other substances in the future. The MDOS obtained here is associated with the rotational motion of the spins in Fig. 1. The MDOS integrated in energy is related to the magnitude of the spin. It was confirmed that its size matches with the magnetic moment measured by magnetic susceptibility. The magnetic moment even in a complicated system, in which the spins may be fluctuating in a certain frequency region, can be determined by this method.

Recently, high-efficient spin current power generation materials have been searched. The guidelines for a ferrimagnetic material are as follows.

1. The clockwise and anticlockwise rotational modes do not overlap.
2. The MDOS in Fig. 2 are high at low energy corresponding to the working temperature range.

These conditions can be satisfied in inelastic neutron scattering experiments. In the future, we will investigate not only magnon but also phonon effects on the spin current power generation by neutron scattering, because of possible strong interactions between them.

References

[1] K. I. Uchida *et al*., Nature (London) **455**, 778 (2008).
[2] T. Kikkawa *et al*., Phys. Rev. B **92**, 064413 (2015).
[3] J. Barker *et al*., Phys. Rev. Lett. **117**, 217201 (2016).
[4] S. Shamoto, T. U. Ito, H. Onishi, H. Yamauchi *et al*., Phys. Rev. B **97**, 054429 (2018).

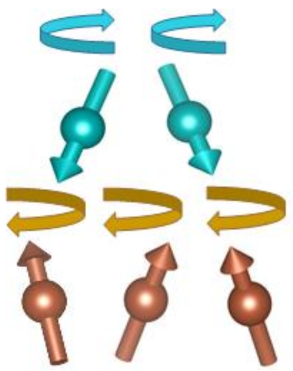

Fig.1. Anticlockwise rotational mode for 5 spins in a YIG sub-lattice is schematically shown. This mode carries a spin current to one direction. This rotational direction in $Y_3Fe_5O_{12}$ is determined based on the crystallographic symmetry [3].

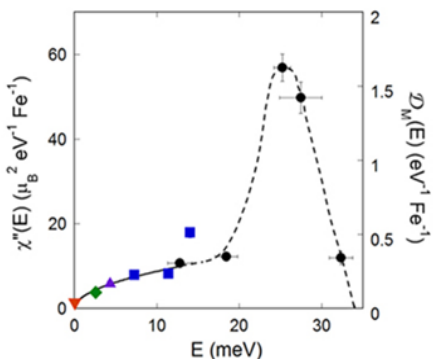

Fig. 2. Magnon density of states ($\mathcal{D}_M$(E)) of YIG obtained by inelastic neutron scattering [4], which is proportional to imaginary part of dynamical spin susceptibility (χ"(E)). The magnitude is one of the important factors for spin current power generation.