Research Group for Spin-Energy Transformation Science

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A spin current is a flow of the angular momentum and becomes the most important issue in spintronics. It will dramatically reduce energy consumption, because of the special property of spin, i.e., its rotational motion is limited in one direction under a magnetic field. Hence, we can expect some interesting functionalities such as spin Seebeck effect, spin motive force, and rectification of heat flow. Using this advantage of spins, we are pursuing our researches based on a new principle to control mechanical, electromagnetic, and thermal energy flows. In this fiscal year, a spin-hydrodynamic generation, which was theoretically predicted by ourselves, has been observed experimentally [1]. This subject is explained in the Research Highlights. Other two interesting results are stated below.

Barnett Effect in Paramagnetic States

The angular momentum is an important quantity of rotating object and a spin of electron is also one kind of angular momentum, although the spin does not literally correspond to the rotating motion. On a rotating frame, the rotational motion plays a role of magnetic field. In 1915, Barnett found that a magnetization is induced in iron by a rotational motion. On the other hand, the Barnet effect has not been so far observed in a paramagnet, because of zero coercivity and small susceptibility, which requires *in situ* observation under rapid rotation.

In this fiscal year, we have successfully observed the Barnett effect in paramagnetic states of gadolinium (Gd) metal with rotational frequencies of up to 1.5 kHz above the Curie temperature [2]. Figure 1 (a) shows the capsule and the Gd sample used in our experiment, and their schematic figures are shown in Fig. 1 (b). The sample used in our study shows ferromagnetic transition at 292.5±0.5 K. The Curie constant is large because of Gd's 4*f* local moment with J=7/2 (S=7/2, L=0). Therefore, magnetic susceptibility around room temperature is high. It allows us to measure small stray fields from the magnetized Gd sample by the rotation, even in paramagnetic states (See also Fig. 1 (b)). The relation between the induced magnetization and the frequency of rotation is plotted in Fig. 1 (c). The ratio of the magnetization and the susceptibility provides an effective magnetic field induced by the rotation. From the gradient of the effective field as a function of the frequency, one can estimate the gyromagnetic ratio of Gd as −29±5GHz/T, which is comparable to −28 GHz/T for an electron in a vacuum or Gd compounds.

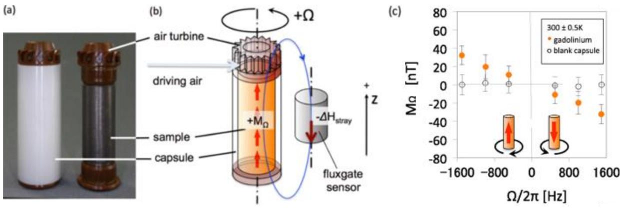
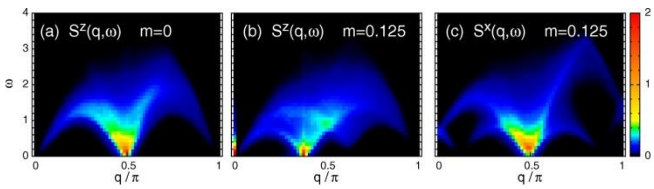


Fig.1 (a) Capsule (left) and Gd sample (right) used in the experiment. (b) Schematic figures corresponding to (a). (c) The magnetization of Gd sample (orange dots) and blank capsule (open circles) as a function of the rotational frequency at 300±0.5 K [2].

Magnetic Excitations of Spin Nematic State in a Frustrated Quantum Spin System

Correlated many-body systems have rich variety of quantum phenomena. A frustrated quantum magnet with competing interactions is an interesting example of correlated many-body system of spins. In general, the combination of frustration and quantum fluctuation prevents a magnetic order and then some novel spin states are stabilized such as spin nemtic state. It is a spin analogue of the nematic liquid crystal and is currently attracting much attention as a novel quantum state in magnetic materials. However, it is not straightforward to observe the spin nematic state, since it does not simply couple to a magnetic nor an electric field. In order to clarify the properties of the spin nematic state, we studied dynamical spin structure factors of a frustrated ferromagnetic chain in a magnetic field using dynamical density matrix renormalization group (DMRG) method [3]. As shown in Fig. 2, the longitudinal mode is gapless, while the transverse one has a gap. This result is in accordance with quasi-long-ranged longitudinal and short-ranged transverse spin correlations, respectively. We further analyzed dynamical quadrupole structure factors to reveal excitation dynamics of the nematic state, since the nematic state is a multiple spin state. We found the gapless quadrupole excitations indicating a quasi-long-ranged quadrupole correlation characteristic to the spin nematic order. We hope that these features could be examined by inelastic neutron scattering experiments in a frustrated magnet such as, $LiCuVO_4$. Furthermore, we should observe gapless excitations in the quadrupole channel as an interesting future problem.

Fig.2 Intensity plots of the dynamical spin structure factor $S^{\alpha}(q,\omega)$ (α=x,



y, z) with wave number q and energy ω calculated by the dynamical DMRG method. (a) z-component of $S^{\alpha}(q,\omega)$ with magnetization, m=0, (b) $S^{z}(q,\omega)$ with m=0.125, and (c) x-component of $S^{\alpha}(q,\omega)$ with m=0.125. Note that, the lowest excitation with finite q is shifted from q/π=0.5 in the case of (b). This is a common character to the spin spiral state.

References

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[2] M. Ono *et al.*, Phys. Rev. B **92**, 174424 (2015).
[3] H. Onishi, J. Phys. Soc. Jpn. **84**, 083702 (2015).