Quantum magnonics in ferromagnetic insulators

Yasunobu Nakamura[1,2]
[1] Research Center for Advanced Science and Technology (RCAST), The University of Tokyo,
4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan
[2] Center for Emergent Matter Science (CEMS), RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

Ferromagnetic resonances (FMR) have been studied for decades. They generate high-quality oscillations of magnetization at microwave frequencies and are applied to various devices such as frequency-stabilized oscillators, narrow-band filters, etc. However, it was very recent that the quest for quantum control and measurement of the collective spin excitations in ferromagnetic materials started.

For FMR at $\omega_m/2\pi$= 10 GHz, a quantum of the magnetostatic oscillation mode, a magnon, has the energy $\hbar\omega_m$ corresponding to the thermal energy of $k_B\times$ 0.5 K. Thus, at 10 mK in a dilution refrigerator, the number of thermally excited magnons in the mode could be negligibly small, i.e., the mode could be in a magnon vacuum.

We use the Kittel mode of a single crystalline yttrium iron garnet sphere and couple the spatially uniform collective spin precession with microwave photons in a cavity, demonstrating strong coupling between the two harmonic oscillator modes.[1)] We next accommodate in the same cavity a superconducting qubit which consists of a Josephson junction and two antenna pads.[2)] The nonlinearity provided by Josephson effect results in an effective two level system, i.e., a quantum bit, with which we control the quantum state of the magnetostatic mode at a single magnon level. We observe an energy level splitting of the qubit excitation due to the interaction with the magnon vacuum via the virtual photon excitation in the cavity. When the magnon and qubit frequencies are detuned, the dispersive interaction between them enables us to count the number of magnons excited in the millimeter-sized sphere one by one.[3)]

We also use this strong dispersive interaction to demonstrate novel protocols for quantum-enhanced sensing of magnons. First, we demonstrate a magnon detection sensitivity of about 10^{-3} magnons/$\sqrt{\text{Hz}}$ by using a simple quantum sensing protocol that relies on dephasing of the qubit from the excitations of magnons in the ferromagnetic crystal. In a second experiment, we entangle the Kittel mode with the qubit through a conditional excitation of the qubit, which we use to demonstrate the single shot detection of a single magnon with a detection efficiency close to 70%, therefore bringing the equivalent of the single photon detector to the field of magnonics.

For a recent review of the progress in the field, see Ref. 4).

Reference
1) Y. Tabuchi *et al.*, Phys. Rev. Lett., **113** (2014) 083603.
2) Y. Tabuchi *et al.*, Science, **349** (2015) 405.
3) D. Lachance-Quirion *et al.*, Sci. Adv., **3** (2017) e1603150.
4) D. Lachance-Quirion *et al.*, APEX, **12** (2019) 070101.