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Quantum microwaves / Micro-ondes quantiques

Quantum magnonics: The magnon meets the superconducting qubit

La magnonique des quanta : Le magnon rencontre le qubit supraconducteur

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ABSTRACT

The techniques of microwave quantum optics are applied to collective spin excitations in a macroscopic sphere of a ferromagnetic insulator. We demonstrate, in the single-magnon limit, strong coupling between a magnetostatic mode in the sphere and a microwave cavity mode. Moreover, we introduce a superconducting qubit in the cavity and couple the qubit with the magnon excitation via the virtual photon excitation. We observe the magnon–vacuum-induced Rabi splitting. The hybrid quantum system enables generation and characterization of non-classical quantum states of magnons.

RÉSUMÉ

Nous appliquons les techniques de l'optique quantique micro-onde aux excitations collectives des spins d'une sphère macroscopique d'un isolant ferromagnétique. Nous mettons en évidence, dans la limite d'une unique excitation magnonique, le couplage fort entre un mode magnétostatique de la sphère et un mode d'une cavité micro-onde. En outre, nous avons ajouté un bit quantique supraconducteur à la cavité, ce qui permet de coupler ce bit quantique au mode de magnon, via l'échange virtuel d'un photon. Nous observons ainsi un anticroisement des fréquences de résonance du magnon et de la cavité. Cette plateforme hybride permet la création et la caratérisation d'états non classiques de magnons.

1. Introduction

The successful development of superconducting qubits and related circuits has brought wide opportunities in quantum control and measurement in the microwave domain [1–6]. In circuit quantum electrodynamics and microwave quantum

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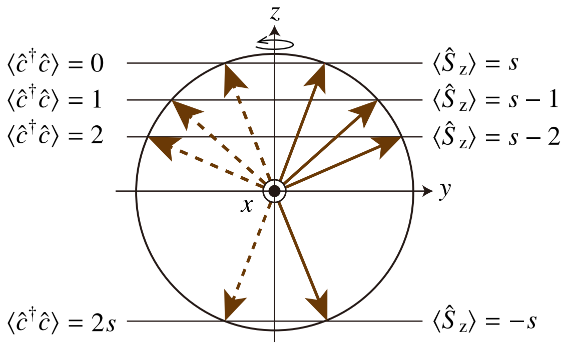

Fig. 1. Relation between magnon number and z-component of total spin. The number of bosons corresponds to the reduction of the total spin.

optics, the bosonic excitations of the electromagnetic modes, i.e. "photons", are handled with high accuracy [7–10].[1] Therefore, it is natural to extend the targets to other quantum mechanical degrees of freedom. The examples are found in recent reports on hybrid quantum systems based on superconducting circuits: for example, paramagnetic spin ensembles [11,12], nanomechanical oscillators [13,14], and surface acoustic waves in a piezoelectric substrate [15] have been coherently controlled via a coupling with a superconducting qubit.

Our goal here is to apply the techniques of microwave quantum optics to collective spin excitations in a ferromagnet. In a similar way to the case of superconductivity, ferromagnetism has a rigidity in its order parameter. The lowest energy excitations are long-wavelength collective spin precessions. We couple the quantum of the collective mode, a magnon, with a microwave cavity as well as a superconducting qubit to reveal its coherent properties in the quantum limit [16,17].

This paper is structured as follows: Sec. 2 reviews the basics of magnons in ferromagnet. In Sec. 3, the hybridization of a magnon and a photon in a microwave cavity is demonstrated. Finally, in Sec. 4, we demonstrate the strong coupling between a superconducting qubit and a magnetostatic mode in a ferromagnetic crystal. The magnon vacuum induces Rabi splitting in the qubit excitation. Summary and outlook are presented in Sec. 5.

2. Magnons in a ferromagnet

2.1. Spin waves

In order to describe spin waves, or collective excitations in ferromagnetic materials, we begin with a simple Hamiltonian:

$$\hat{\mathcal{H}} = -g\mu_B B_z \sum_i \hat{S}_i^z - 2J \sum_{\langle i,j \rangle} \hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_j \tag{1}$$

where the first term represents the Zeeman energy and the second one is the nearest-neighbor exchange interaction. The sum in the second term is taken over the pairs of the neighboring spins. $\hat{\mathbf{S}}_i$ is the Heisenberg spin operator for the i-th site, g is the g-factor, μ_B is the Bohr magneton, B_z is the static magnetic field along the z axis, and J is the exchange integral. J takes positive values for ferromagnetic materials, leading to the ferromagnetic ground state, where all the spins are aligned along the z axis.

We can express the Heisenberg operators in terms of the bosonic operators $\hat{c}_i$, $\hat{c}_i^\dagger$ by using the Holstein–Primakoff transformation [18]:

$$\hat{S}_i^+ = \hat{S}_i^x + \mathrm{i}\hat{S}_i^y = \sqrt{2s}\left(1 - \frac{\hat{c}_i^\dagger \hat{c}_i}{2s}\right)^{1/2} \hat{c}_i \tag{2}$$

$$\hat{S}_i^- = \hat{S}_i^x - \mathrm{i}\hat{S}_i^y = \sqrt{2s}\,\hat{c}_i^\dagger \left(1 - \frac{\hat{c}_i^\dagger \hat{c}_i}{2s}\right)^{1/2} \tag{3}$$

$$\hat{S}_i^z = s - \hat{c}_i^\dagger \hat{c}_i \tag{4}$$

where s is the total spin on each site. The meaning of this transformation is illustrated in Fig. 1. We find from Eq. (4) that the number of the bosons corresponds to the reduction of the z-component of the total spin.

[1] To be more precise, we may say that surface plasmon polaritons, i.e., quanta of the hybridized modes of the surface charge density waves on the electrodes and the electromagnetic waves in the vacuum, are manipulated in the circuits.