Indirect Interactions between Magnets

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Status

The exchange interactions between electron spins in condensed matter generates a rich variety of magnetic order. It becomes exponentially small at larger than atomic distances, so different magnets interact by exchange only when in direct contact. The weaker dipole interaction generates forces between macroscopic magnets that decay algebraically with distance. Magnets can also interact indirectly through a non-magnetic medium. Mobile electrons in metals mediate an oscillatory RKKY non-local exchange interaction over nanometers. The coupling by non-equilibrium spin currents through metal spacers can reach over micrometers. The exchange of spin waves synchronizes magnetic oscillators. Microwave photons in high-quality cavities are supremely suited to communicate spin information because of their coherence over large distances and the strong interaction of spin ensembles such as ferromagnets with the AC magnetic fields [1,2]. Other waveforms such as magnon and phonons also generate indirect interactions between small magnets over relative large distances [3,4]. In this roadmap article, we outline the interest of letting two or more ferromagnets interact in cavities or wave-guides for different mediating waveforms but with emphasis on microwaves.

In free space, magnets interact by the magneto-dipolar interaction, which is very weak for typical sub-nm magnetic spheres at cm distances. However, they may couple strongly over large distances by exchanging virtual photons in cavity modes. Interpreting the collective Kittel mode of a single magnet as a magnonic hydrogen atom, an interacting pair forms a magnonic hydrogen molecule with hybridized orbitals of even and odd symmetry [5]. When probed by an even cavity mode, microwave spectroscopy detects the first “bright” mode, but not the second “dark” one [1]. The (sub-radiant) magnons in the dark mode do not suffer from radiative damping and have longer decay time, which might be useful for quantum information storage [1]. The indirect interaction between magnets provides a large playground since the cavity as well as position, size and type of the magnets is arbitrary. Adding non-magnetic, but optically active structures and materials, is another important option. The task to systemize various configurations, to find new hybridizing mechanisms, and search for applications is a challenge that has only just begun.

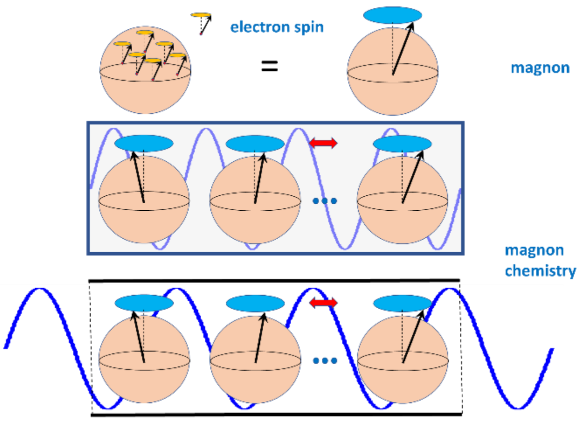

Figure 1. The collective dynamics of a ferromagnetic particle (Kittel magnon) can be interpreted as ground state of a bosonic atom. The interaction between different atoms, enhanced by the exchange of photons in open or closed cavities, leads to collective delocalized states.

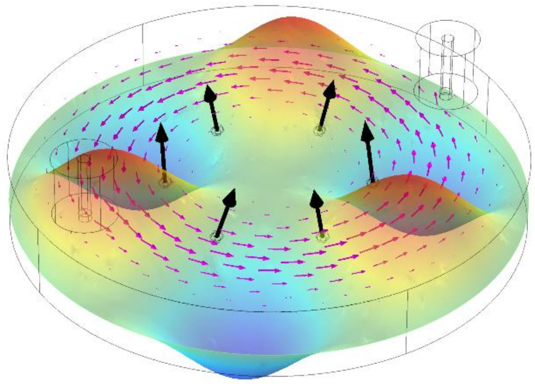

Figure 2. Numerical simulation of six magnetic spheres on a circle inside a disk-shaped microwave cavity fed by attached ports. At resonance, the magnetizations (black arrows) precess coherently in the presence of a unidirectional photon current as illustrated by the Poynting vector field (magenta arrows). The colored background is the electric field component in the perpendicular direction. We interpret this system as a chiral magnonic benzene molecule (W. Yu et al., unpublished)

Current and Future Challenges

Customizing cavities: Cavities come in different shapes and types. The ideal microwave cavity is a closed box of high-quality metal that confines photons without significant losses. Small Orifices do not disturb the system significantly and act as non-invasive input and output terminals that allow measuring the properties of the hybrid system in terms of the microwave transmission and reflection coefficients. When magnetization damping is small as well, the cavity + load system approximately conserves energy and the system Hamiltonian is (almost) Hermitian. The magnon-photon coupling is then coherent, and photon and magnon levels repel each other when tuned to degeneracy. Coplanar waveguides are open cavities that offer greater flexibility, but are leaky, i.e. have a smaller quality factor. Waveguides are intrinsically open cavities that channel the free flow of microwaves with associated radiative damping. Dissipation may change the qualitative physics since a non-Hermitian Hamiltonian governs the non-local interaction between magnets [6].

The indirect coupling already modifies the ground state. When not at the minimum of the free energy, mechanical and magnetic torques and forces arise that can be modulated by the magnetic configuration and the frequency detuning. Heat current flow in the presence of temperature differences in the cavity. Feeding the cavity with microwaves from external sources, either via the input and output ports or local coils that address individual magnets [1], can drive the system into highly excited states [7].

Cavities or resonators can also confine optical photons, but the domination electric field coupling is relatively weak. An interesting challenge is the use of cavities in the intermediate Thz radiation regime. Thin films confine phonons normal to thin films where they may form phononic spin valves [4], while magnon cavities can be induced by nanostructures on magnetic thin films [3].

Loading cavities: We may fill the cavities by magnets in different numbers and structural as well as magnetic configurations. Figure 1 shows as an example a collinear magnonic benzene molecule driven by a microwave feed from the input port. We are not limited to ferro- or ferrmagnets, but may use antiferro- and paramagnets. The magnonic atoms may "react" with other particles made from, e.g., ferroelectrics, superconductors, Josephson qubits [6], metamaterials, or devices such as magnetic tunnel junctions.

Chiral interaction: In the absence of relativistic effects, the angular and linear momentum of photons, phonons, and magnons waves are in general independent. However, chirality emerges in Damon-Eshbach surface spin waves or by spin waves excited by magnetodipolar stray fields [3]. Cavities or waveguides induce admixtures of TM and TE modes that generate local chirality at special lines. When the mediating waves are chiral the indirect coupling between magnets is unidirectional. A consequence is the accumulation of magnons at the edge of a chain of magnets in a cavity [7]. It is then possible to design chiral magnonic molecules analogous to conventional aromatic molecules, but with non-reciprocal magnon couplings and persistent currents, facilitating the design of novel on-chip microwave isolators and circulators. Since spin waves in thin film can be chirally excited by magnetic stray fields, similar games become possible on a much smaller scale. The acoustic Rayleigh surface waves display rotation-momentum coupling and generate novel indirect couplings [8].

Toroidal moment: The toroidal dipole moment or anapole is a parameter to describe the electromagnetic far field, which is independent from the magnetic and electric dipoles [9]. Spatially distributed magnets can contribute either static or dynamic toroidal multipoles, which have peculiar response and radiating properties. As discussed above, in a microwave cavity loaded by magnets, chiral spin currents may flow by means of cavity photon exchange. We anticipate that an exchange-strained circular spin texture generates equilibrium spin currents and associated toroidal moments, while injected microwaves in the configuration of Figure 1 generates a giant dynamic anapole.

Towards quantum: Strongly coupled microwave photons can drive a weakly damped magnonic system easily into the non-linear regime, which is an important prerequisite for interesting quantum effects. Non-linearities generate highly entangled magnon-photon states or generate tripartite entanglement between magnons, photons and phonons [10].

Concluding Remarks

Magnons in spatially separated magnets may hybridize by the coherent exchange of (quasi)particles such as photons, phonons, and continuum magnons. Coupled magnet assemblies form very flexible devices on various length scales. AC and DC magnetic fields easily manipulate their collective bosonic excitations, offering a unique platform to study quantum effects and test new functionalities needed for next-generation information technologies.

Acknowledgements

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