Project A7

Collective effects and instabilities of a magnon gas

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The project addresses fundamental issues in the collective dynamics of magnon gases as model systems of interacting quasi-particles. Magnon gases have been recognized as an excellent model environment for the experimental investigation of collective classical and quantum macroscopic properties of bosonic systems. The phenomenon of high-temperature Bose-Einstein condensation of magnons in a magnetically ordered medium is one demonstration of this. The character of magnon-magnon interactions within magnon gases and condensates as well as their static and dynamic spectral properties can be effectively controlled using a combination of static and microwave frequency external magnetic fields. An additional controllability is possible due to quantization of both energy and momentum in the magnon spectra in a patterned magnetic medium. The main goal of our project is to study the phase transition processes resulting in the formation of quantum macroscopic states of a magnon gas and to understand the role of multi-magnon interactions in the properties of these correlated states of matter in comparison with dynamics of ultracold quantum gases and quantum spin systems. This aim will be achieved through the investigation of dynamic and kinetic interaction processes in magnon gases whose density is controlled by external electromagnetic pumping. The main experimental method using to measure the characteristics of magnon gases and condensates is space-, time and phase-resolved Brillouin light scattering (BLS) spectroscopy.

Magnon Gases and Condensates

In ferromagnetic materials atoms having unpaired electrons act as individual magnets. Their magnetism is mostly caused by the magnetic moments of the uncompensated electron spins. Since these atomic magnets tend to be oriented in the same direction due to quantum-mechanical exchange interaction, a macroscopic magnetic moment appears. As the atoms strongly interact, a reversal of a single atomic magnetic moment is not spatially localized but spreads through the solid as a wave of discrete magnetic momentum transfer. This wave is known as a spin wave, and in frame of the second quantization it is associated with a quasi-particle called magnon. Weakly interacting magnons can be considered as a gas of magnetic bosonic quasi-particles and, therefore, this is called a magnon gas.

Recently magnon gases have been recognized as an excellent model environment for the experimental investigation of collective classical and quantum macroscopic properties of bosonic systems. Its potential is due to the wide controllability of the magnon density as well as of the spectral properties influencing the magnon-magnon interaction. For example, the dispersion branch of a magnon gas can be frequency shifted or even drastically modified by change in the strength or orientation of a bias magnetic field. The magnon population density can be effectively controlled by means of electromagnetic parametric pumping (see Gurevich and Melkov, Magnetization Oscillation and Waves, CRC, Cleveland, 1996). In the simplest case, one photon of the pumping electromagnetic field excites two magnons with half the energy/frequency that propagate in opposite directions. Such a mechanism creates a huge quantity of phase-correlated magnons, which are called a condensate of photon-coupled magnon pairs. The behavior of parametrically created magnon condensates, of gaseous magnon phases, and of Bose-Einstein condensates (BEC), which can be formed at the lowest energy state of a magnon gas, constitutes a hot research topic.

The main goal of our work is to study the phase transition processes resulting in the formation of quantum macroscopic states of a magnon gas and to understand the role of magnon-magnon and magnon-phonon interactions in the properties of these correlated states of matter in comparison with the dynamics of ultra-cold quantum gases and quantum spin systems. We investigate the dynamics of the magnon system in a low-damping magnetic insulator (yttrium-iron-garnet, YIG) using wavevector- and time-resolved Brillouin light scattering (BLS) spectroscopy with special attention on the pump-free evolution of the magnetic medium after pumping.

Experimental setup

The BLS spectroscopy is based on the interaction of photons with magnons and phonons. The interaction can be understood as an inelastic scattering process of the incident photons with magnons, taking into account energy and momentum conservation. The detection of the inelastically scattered photons, i.e. the separation from the elastically scattered photons and the determination of the transferred energy, requires an interferometry technique with extremely high contrast and sensitivity. In our laboratory we implemented the (3+3) Tandem-Fabry-Perot-Interferometer. It consists of two Fabry-Perot interferometers (FPI), each one passed three times by the inelastically scattered light. This approach results in a contrast better than 10^{10} for the separation of the elastically and inelastically scattered photons in a frequency range from 500 MHz up to 1 THz.

The time- and wavevector-resolved BLS setup consists of permanent magnet, which are mounted on top of a rotating plate. The tuning of the field between the two poles is realized by iron shunts mounted parallel to the poles and a small electromagnet. The YIG sample is placed on a microstrip resonator, which is fabricated on top of an alumina substrate. A microwave source, a switch, a power amplifier and a Y-circulator are connected to the circuit in order to parametrically drive the magnon system.

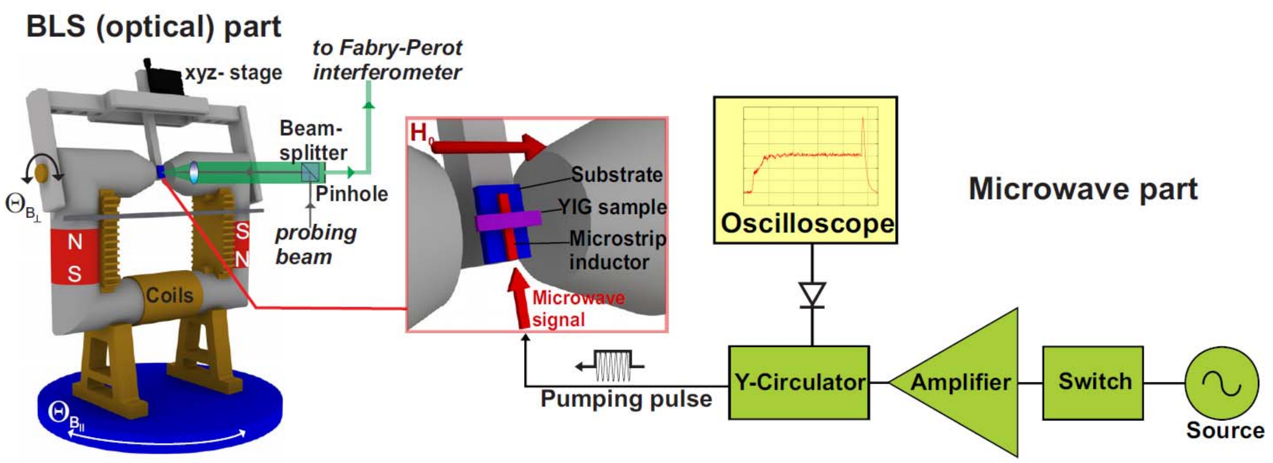

Figure 1. Sketch of the experimental setup.

Recent results

1. We have already shown that the dynamics of the free-evolving magnon BEC can be properly understood in the frame of a model of a spectrally non-uniform magnon temperature. As a specific outcome, a spectrally localized overheating of the condensed magnon gas up to 30'000K was found. The last year we presented the experimental results, which allow us to conclude that the chemical potential of a magnon gas is a spectrally dependent quantity as well: We were able to show the condensation of magnon-phonon quasi-particles (so called magneto-elastic mode, MEM) at a *virtual* energy minimum, whose frequency position is determined by weakening of magnon-phonon interaction. It is remarkable that these quasi-particles have an extremely high group velocity, and, thus, are very sensitive to the spatial configuration of the pumping field.

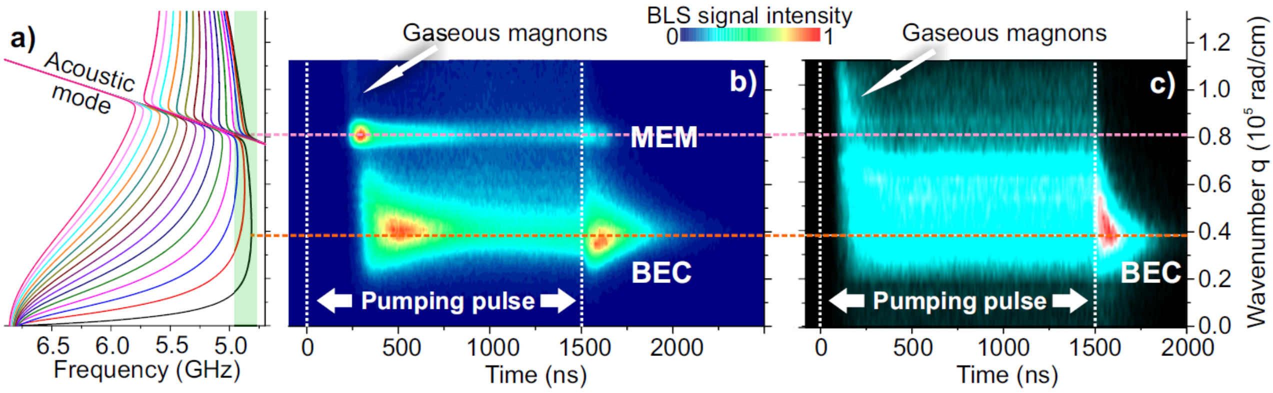

Figure 2. Magnon spectrum and its population under different pumping conditions. a) Spin-wave dispersion branches hybridized with a transversal acoustic mode in an in-plane magnetized YIG film. The bias magnetic field is H_0 =1710 Oe. The calculation is done for backward volume spin waves propagating along the magnetization direction. The first fifteen thickness spin-wave modes are shown. b) Temporal dynamics of the magnon gas density measured in the case of spatially uniform parametric pumping. Resonator width is 500 µm. The BLS data are collected in the frequency band of 150 MHz near the bottom of the magnon spectra (shadowed band in panel (a). c) The same dependence as in (b) but measured for a pumping area width of 50 µm.

2. The thermalization of a condensate of photon-coupled magnon pairs was studied in a phase space and a dominant role of short wavelength exchange magnons to the population of the lowest energy states of the magnon spectrum was experimentally demonstrated.
3. Microwave emission from a parametrically pumped ferrimagnetic YIG film was studied versus the magnon density evolution, which was detected by Brillouin light scattering spectroscopy. It has been found that the shutdown of external microwave pumping leads to an unexpected effect: The conventional monotonic decrease of the population of parametrically injected magnons is accompanied by an explosive behavior of electromagnetic radiation at the magnon frequency. The developed theory shows that this explosion is caused by a nonlinear energy transfer from parametrically driven short-wavelength dipolar-exchange magnons to a long-wavelength dipolar magnon mode effectively coupled to an electromagnetic wave.
4. In order to understood the behavior of parametrically driven magnon gas in micro-sized magnetic samples with a sparse magnon spectrum we successfully realized and studied by a microscopic BLS technique the localized parametric generation of spin waves both in longitudinally [2] and transversally magnetized $Ni_{81}Fe_{19}$ waveguides.

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