4.2 Magnon supercurrent in a magnon Bose-Einstein condensate subject to a thermal gradient

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Bose-Einstein condensation can be achieved either by decreasing the temperature of a boson gas or by increasing its density. The latter method is especially applicable to gases of weakly interacting quasi-particles like magnons, whose number can be effectively controlled by external electromagnetic pumping [1]. When a spin system is pumped, and when the injected magnons thermalize through scattering processes conserving both their number and the total energy, a Bose-Einstein condensate (BEC) may be formed at the lowest energy state of the energy-momentum spectrum. As the magnon BEC is localized in the global energy minimum, its group velocity is exactly zero and no energy transfer is associated with the magnon condensate. However, such a transfer is still possible due to the excitation of a magnon supercurrent [2–4], which can be driven by a gradient in the phase of the wavefunction of the magnon BEC. Here we provide experimental insight into the evolution of a magnon BEC in a thermal gradient generated by local laser heating, and we show that its transitional behavior can be understood using the concept of a magnon supercurrent.

Fig. 1: a) Schematic illustration of the experimental setup. In the upper part of the figure the microwave circuit consisting of a microwave source, a switch and an amplifier is shown. This circuit drives a microstrip resonator, which is placed below the in-plane magnetized YIG film. The light from a solid-state laser is chopped by an acousto-optic modulator and guided through a beam splitter (BS) and a mirror (M) to the YIG film. There it scatters inelastically on magnons, and the frequency shifted component of the scattered light is selected by the tandem Fabry-Pérot (TFP) interferometer, detected, and analyzed in time. The time diagram b) presents relative time positions of the applied microwave pump pulse, the laser pulse, and the detected BLS signal.

We study the temporal evolution of a magnon BEC in a single-crystal yttrium iron garnet (YIG, $\text{Y}_3\text{Fe}_5\text{O}_{12}$) film by time-resolved Brillouin Light Scattering (BLS) spectroscopy [5]. The experimental setup, which consists of a YIG film, a microwave circuit, and a BLS system is schematically shown in Fig. 1a. The in-plane magnetized YIG sample is 5.6 $\mu$m thick, 5 mm long and 1 mm wide. The microwave pumping circuit consists of a microwave source, a switch and an amplifier. This circuit drives a 50 $\mu$m wide microstrip resonator, which is placed below the YIG film and tuned to
the pumping frequency of $f_p = 13.06\,\text{GHz}$. Magnons are injected into the YIG sample via parallel parametric pumping at a frequency of $f_p/2$. The strength of the bias field $\mu_0H = 169.0\,\text{mT}$ is chosen to allow for magnon injection at the ferromagnetic resonance frequency (FMR), where the parallel pumping achieves its highest efficiency [6].

In our experiment, a focused laser beam combines the role of the magnon probe in the BLS experiment with the role of the local sample heater. The heating time is adjusted by chopping the probing laser beam using an acousto-optic modulator (AOM). The laser pulse duration $\tau_{\text{laser}}$ is varied between $6\,\mu\text{s}$ to $80\,\mu\text{s}$ with a repetition time of $1\,\text{ms}$, allowing both for magnetic and temperature equilibration of the YIG film. The modulated probing beam is focused onto the surface of the YIG film sample in the middle of the microstrip resonator, where it has a maximal peak power of $9.5\,\text{mW}$. The radius $r$ of the focal point is about $10\,\mu\text{m}$.

Fig. 2: Temperature dependent temporal dynamics of the magnon BEC. Panel a) shows the time-resolved Brillouin light scattering intensity for different uniform temperatures of the YIG film. The influence of the temperature on the spin-wave dispersion is shown in b).

In order to understand the temperature influenced magnon BEC dynamics one first needs to separate the effects caused by the spatially uniform change of a sample temperature from those caused by the formation of a temperature gradient. Therefore, in the first experiment we combined a low-power BLS probing light beam with an uniform air heating of the YIG film. Figure 2a shows the typical dynamics of the magnon BEC in this case. In course of the pump action, the magnon density, which is proportional to the intensity of the BLS signal, increases and saturates. After the parametric pumping is switched off, the magnon density jumps up due to the efficient BEC formation intensified by the evaporative cooling of the freely evolving magnon gas [7]. Afterwards the magnon density exponentially decreases due to conventional spin-wave relaxation. This behavior is the same for all temperatures in our experiment. Some decrease in the steady-state magnon density at higher temperatures is related to the lower efficiency of the parametric pumping. Due to a lowered saturation magnetization at higher temperatures the spectral branch of parametrically excited magnons shifts towards lower frequencies, see Fig. 2b. This shift increases the wavenumber of the injected magnons and, consequently, the threshold power of the parametric generation [6].

Now we focus on the temperature gradient dependent behaviour of the magnon condensate. Figure 3a shows the evolution of the magnon density at the bottom of the spin-wave spectrum for four different heating times, i.e. for four values of the temperature gradient, at a laser power of $P_{\text{laser}} = 9.5\,\text{mW}$. For comparison, the black curve presents the time-dependent magnon dynamics measured using a much lower laser power of $0.4\,\text{mW}$. Similar to Fig. 2a, due to the pronounced
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Fig. 3: a) Temporal dynamics of the magnon BEC under local laser heating. The increase of the laser pulse duration, and thus the heating time, leads to a faster relaxation of the BEC phase. The relaxation time of the residual gaseous magnons is independent of the heating. b) Calculations are done in accordance with Eq. 1.

BEC formation, the magnon density rises sharply after the microwave pumping pulse is switched off [7]. Afterwards, the magnon density decreases. In the case of the low-power laser probing this decrease has an exponential form with a characteristic decay time $\tau$ of 240 ns, which corresponds well to the conventional values of a linear magnetic damping in YIG films [8].

At higher laser power, the observed decrease in the magnon density cannot be described by one single exponential function anymore. Two different regimes of the magnon decay are clearly visible from the slopes of the BLS waveforms presented in Fig. 3a. These regimes are marked by the light gray and dark gray backgrounds. In the first regime, at high BLS intensities, the decay of the magnon density depends on the heating duration, i.e., on the temperature gradient in the laser focal point. In the second regime, at low BLS intensities, this decay is temperature independent and its rate coincides with the one observed in the low-laser-power experiment. It is remarkable that for all heating durations, the transition between these two decay regimes occurs at approximately the same magnon density level, which can be associated with the transition from the condensed to the gaseous magnon phase.

We interpret these findings as follows. The magnon BEC is a spontaneously established coherent ground state, which possesses well-defined frequency, wavevector, and phase [9]. The laser heating locally changes the saturation magnetization and, thus, induces a weak frequency shift $\Delta \omega$ between different parts of the magnon condensate. In the course of time, this frequency shift results in an increasing phase gradient in the magnon BEC. As a result, a phase-gradient-induced magnon current or, in other words, a magnon supercurrent, flowing out of the hot region of the focal point, is excited. This efflux reduces the density of the magnon BEC in the probing point. After some time, the decrease in the magnon density results in the disappearance of the condensate, and thus in the disappearance of the supercurrent. Consequently, this leads to the restoration of the conventional relaxation dynamics associated with a residual incoherent magnon phase.

The magnon efflux can be written as $\Phi = 2n_c v_{sc}/r$, where $n_c$ is the magnon BEC density, $v_{sc}(\Delta \phi) = \hbar \Delta \phi / m$ is the velocity of the phase-induced magnon flow, $r = S/V$ is the radius of the heated cylindrical volume $V$ inside of the YIG film, and $S$ is the lateral area of this volume. $\hbar$ and $m = \hbar/2\eta$ are the Planck constant and the effective magnon mass, respectively. $\eta$ is the exchange stiffness constant. The phase difference $\Delta \phi = \Delta \omega \cdot (t - t_0) / r$ increases along the time interval $t - t_0$ after the pump action is stopped at the moment of time $t_0$, see Fig. 3b.
The supercurrent influenced BEC dynamics can be described by a rate equation, which has already been used in Ref. [7] to explain the upward jump in the BEC density \( n_c \) after the end of the pump pulse, if we include an additional decay term associated with the efflux \( \Phi = A(t - t_0) \):

\[
\frac{1}{\Gamma} \frac{dn_c}{dt} = -\lambda n_{in} - n_c \cdot \left[ 1 - A \Theta(t_0)(t - t_0) e^{-\frac{t-t_0}{T_{ph}}} \right] + n_g^3.
\] (1)

The temperature gradient dependent parameter \( A \) is given by the equation \( A = (2\hbar \Delta \omega)/(m \Gamma r^2) \). The relaxation frequency \( \Gamma \) corresponds to the conventional magnon decay, parameter \( \lambda \) defines the influence of the inflow of parametric magnons \( n_{in} \) on the BEC formation, \( \Theta(t_0) \) is the Heaviside function, and \( n_g \) is the gaseous magnon density. The time-dependent exponential function in the new decay term contains a phase relaxation time \( T_{ph} \) and, thus, takes into account the loss in the coherency of the magnon BEC related to its finite lifetime. The value of \( T_{ph} \) is comparable with \( \Gamma \) and must decrease with increase of the sample temperature.

One can see from Fig. 3b that the theoretical curves, which are calculated in accordance with the proposed model, coincide with the experimental data (see Fig. 3a) very well. As it is expected, the parameter \( A \) increases and the time \( T_{ph} \) decreases with increase in the laser power and the heating duration. Thus, the reported results provide further experimental and theoretical evidence of a magnon supercurrent at room temperature.

Financial support from the Deutsche Forschungsgemeinschaft within the SFB/TR 49 and from the State Fund for Fundamental Research of Ukraine (SFFR) is gratefully acknowledged. D.B. is supported by a fellowship of the Graduate School Material Sciences in Mainz (MAINZ) through DFG funding of the Excellence Initiative (GSC-266).

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