Superfluidity in condensate of Magnons

Experiment and Theory

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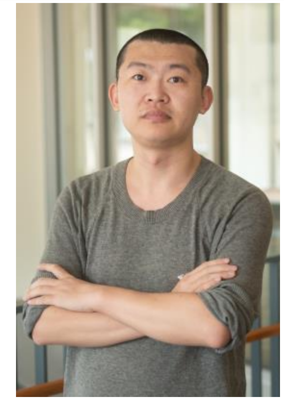

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Brief outline

1. Introduction: Bose-Einstein condensation in YIG films. Experiment
2. Theory of BEC for free and interacting magnons. Problem of BEC stability.
3. Superfluidity of magnons.
4. Experiment with inhomogeneous field.
5. Conclusions.

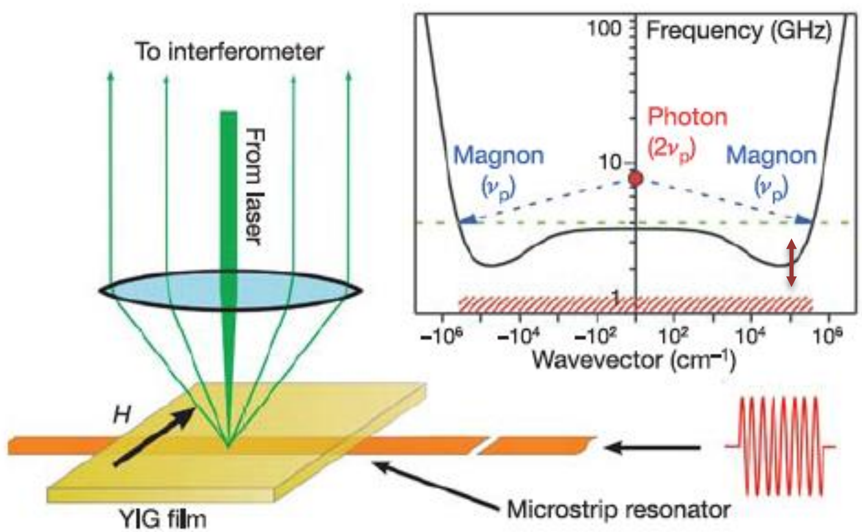
1. Bose-Einstein condensation of magnons in YIG-Experiment

nature Vol 443|28 September 2006|doi:10.1038/nature05117

LETTERS

Bose–Einstein condensation of quasi-equilibrium magnons at room temperature under pumping

S. O. Demokritov[1], V. E. Demidov[1], O. Dzyapko[1], G. A. Melkov[2], A. A. Serga[3], B. Hillebrands[3] & A. N. Slavin[4]



$\hbar\omega_p < 2\Delta$ → Decays are forbidden → number of magnons is conserved

1. Bose-Einstein condensation of magnons in YIG-Experiment

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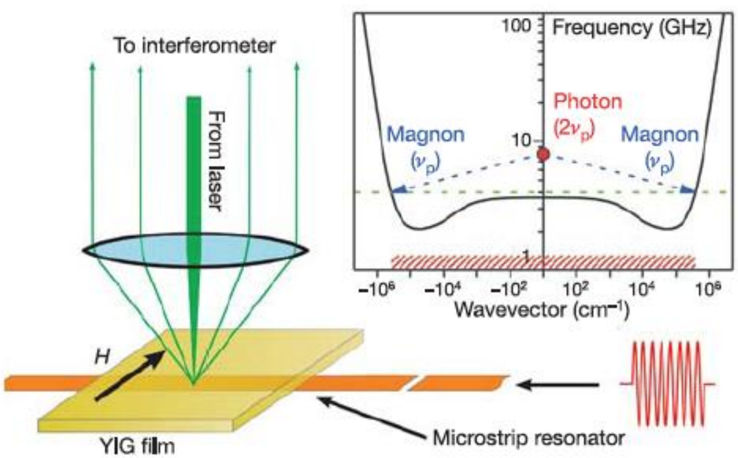
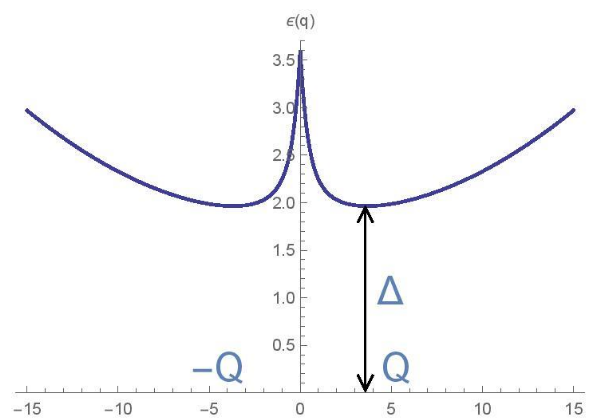




$$\omega(k) = \gamma\sqrt{(H + Dk^2)\big(H + Dk^2 + 4\pi M F(kd)\big)}\ ;\ F(x) = \frac{\pi^2}{x^2}$$

Kalinikos, Slavin, Rezende, Sonin

D – exchange constant; *M* – magnetization;
$\hbar\gamma H$ – Zeeman energy

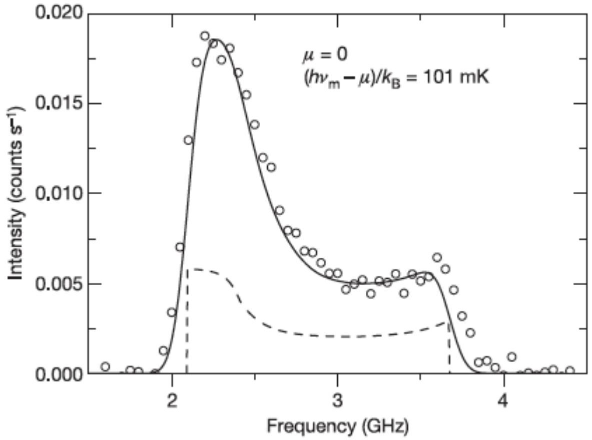


Figure 2 | BLS spectrum of thermal magnons recorded without pumping. The reduced density of states, $\tilde{D}(\nu)$, obtained from the fit of the experimental data (solid line) using equation (1) with the zero chemical potential, μ, is shown by the dashed line. ν_m is the minimum frequency of magnons, h is Planck's constant, and k_B is the Boltzmann constant.

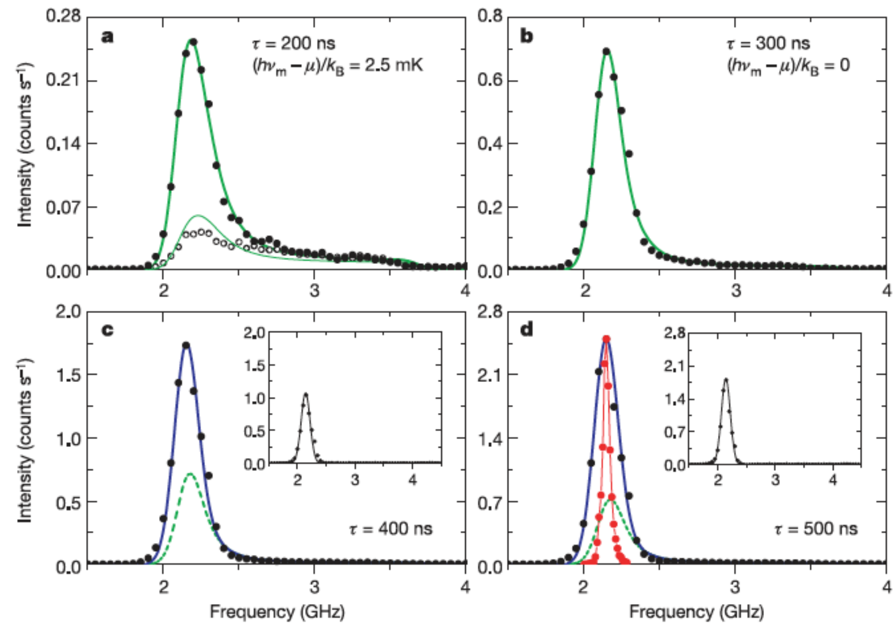


Figure 3 | BLS spectra from pumped magnons at different delay times, τ. **a**, τ = 200 ns; **b**, 300 ns; **c**, 400 ns; and **d**, 500 ns. Black and red filled circles (all panels) show data points recorded at pumping power P = 5.9 W, whereas open circles (panel **a**) represent the data recorded at P = 4 W. Green solid lines in **a** and **b** show the results of the fit of the spectra based on equation (1) with the chemical potential being a fitting parameter. The fit of the spectra in **c** and **d** (blue solid lines) are the sums of the magnon density calculated using equation (1) (green dashed line) with $\mu = h\nu_m$ and the magnon density due to the singularity at $\nu = \nu_m$. Red circles in **d** indicate data obtained with a resolution of 50 MHz; red line is a guide for the eye, connecting the red circles. Insets in **c** and **d** illustrate the difference between the corresponding raw spectra and that at τ = 300 ns; axes as main panels.

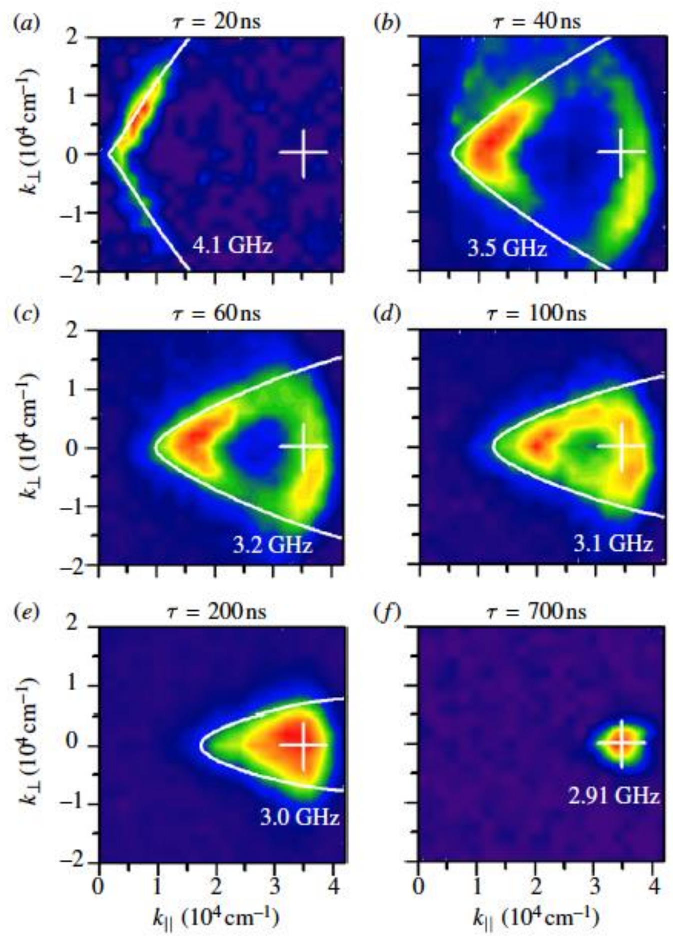
Room temperature!

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Phil. Trans. R. Soc. A (2011) **369**, 3575–3587
doi:10.1098/rsta.2011.0128

Bose–Einstein condensation of spin wave quanta at room temperature

By O. Dzyapko[1], V. E. Demidov[1], G. A. Melkov[2] and S. O. Demokritov[1,*]



SCIENTIFIC REPORTS

OPEN

SUBJECT AREAS:
MAGNETIC MATERIALS AND DEVICES
QUANTUM PHYSICS

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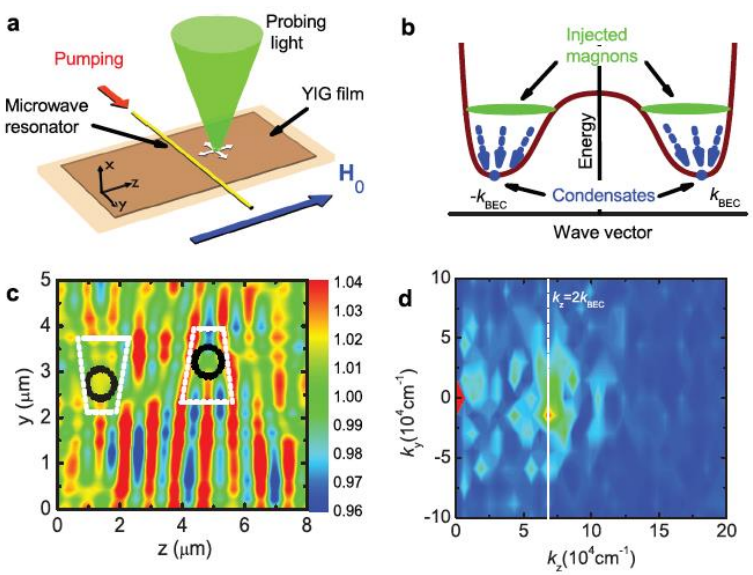
29 June 2012

Spatially non-uniform ground state and quantized vortices in a two-component Bose-Einstein condensate of magnons

P. Nowik-Boltyk[1], O. Dzyapko[1], V. E. Demidov[1], N. G. Berloff[2] & S. O. Demokritov[1]



The BLS signal is proportional to

$$dM_z \ \mu - \left| c_Q e^{iQz} + c_{-Q} e^{-iQz} \right|^2$$

$$c_{\pm Q} = \sqrt{n_\pm} e^{i\phi_\pm}$$

$$-\delta M_z \propto n_+ + n_- + 2\sqrt{n_+ n_-}\cos(2Qz + \phi_+ - \phi_-)$$

2. Theory of BEC of free and interacting magnons

Frequency of pumped magnons is less than doubled gap frequency
➔ the number of spin waves is conserved (almost)

Bun'kov and Volovik, J. Low Temp. Phys. **150**, 135, 2008

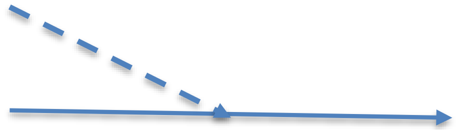
Pumping establishes a stationary number N_p of magnons:

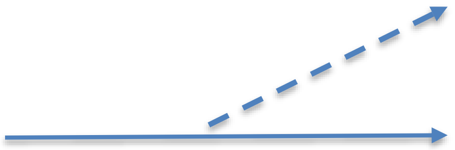
$$N_p = \frac{2W_p\tau_l}{\hbar\omega_p}$$

Pumping power

Lifetime

Low energy magnons relax to a metastable thermal equilibrium with non-zero chemical potential. Quantization.





Finite lifetime of low-energy magnons is due to their absorption by thermal magnons
It is long since this process is induced by dipolar interaction and has small statistical weight because of small Mach angle and strong orthogonality of eigensates.

Stationary number N_p of magnons at pumping:

$$N_p = \frac{2W_p\tau_l}{\hbar\omega_p}$$

Low energy magnons relax to a metastable thermal equilibrium with non-zero chemical potential during the relaxation time $\tau_r \ll \tau_l$

Magnon occupation numbers before pumping $f(\varepsilon) = \frac{T}{\varepsilon}$

After pumping $f(\varepsilon) = \frac{T}{\varepsilon - \mu}$

Total density of pumped magnons

$$n_p(\mu) = \frac{W_p\tau_l}{\hbar\omega_p V} = \int_{\Delta}^{\infty}\left(\frac{T}{\varepsilon-\mu} - \frac{T}{\varepsilon}\right)\nu(\varepsilon)d\varepsilon$$

Density of states

Energy gap

$\mu < \Delta = 2\mu_B H$

$\mu = \Delta$ -- equation of condensation line

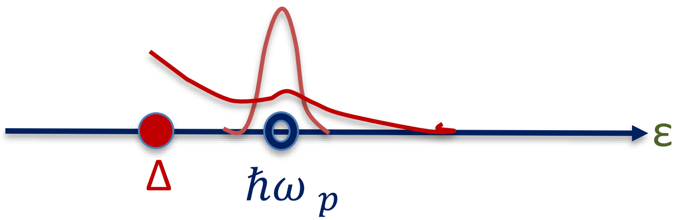
Critical pumped density: $n_{pc} = \int_{\Delta}^{\infty} \left(\frac{T}{\varepsilon - \Delta} - \frac{T}{\varepsilon} \right) \nu(\varepsilon) d\varepsilon$

When the pumped density n_p exceeds critical value the remainder falls in condensate:

$$n_{cond} = n_p - n_{pc} \qquad n_p = \frac{W_p \tau_l}{\hbar \omega_p V}$$

The number of magnons in condensate is also determined by pumping power

Why BECM is possible at room temperature?



Pumped magnons remain in the range of energy $\sim\Delta \ll \mathrm{T}$

Pumped energy $\int_{\Delta}^{\infty} \varepsilon \left(\frac{T}{\varepsilon - \Delta} - \frac{T}{\varepsilon} \right) \nu(\varepsilon) d\varepsilon$ diverges.

It goes to thermal magnons and changes temperature, but by very small amount

C. Sun, T. Nattermann and V.P., J. Phys. D: Appl. Phys. **50**, 143002 (2017)

BEC of interacting magnons

SCIENTIFIC REPORTS

OPEN

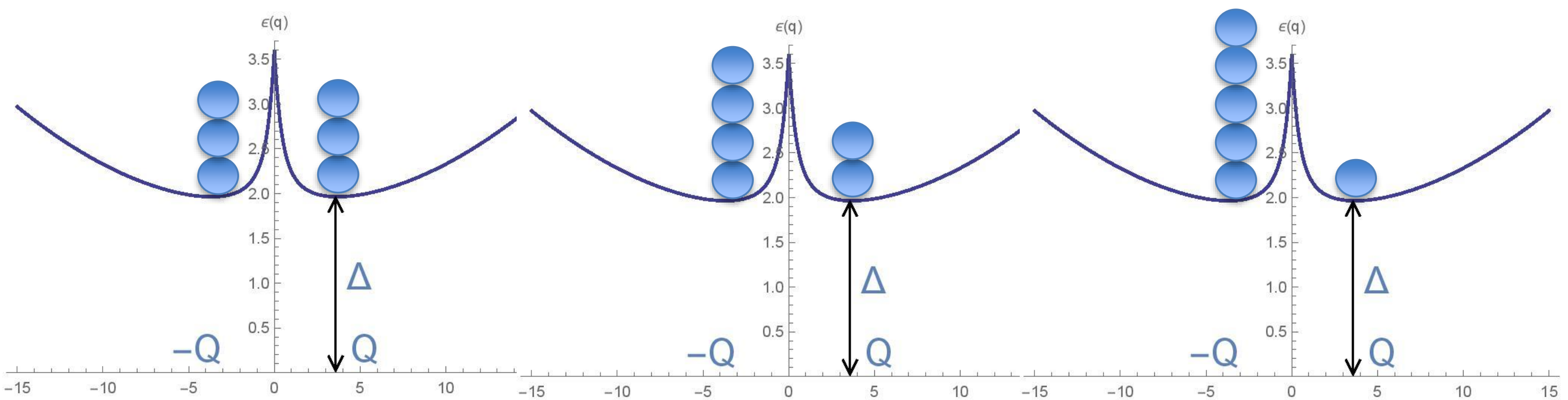
Phase Diagram for Magnon Condensate in Yttrium Iron Garnet Film

SUBJECT AREAS:
BOSE-EINSTEIN CONDENSATES

Fuxiang Li[1], Wayne M. Saslow[1] & Valery L. Pokrovsky[1,2]

Published
4 March 2013

The relocation of free magnons from one condensate to another does not change total energy



The degeneration is lifted by interaction of magnons

Interaction energy of fourth order in condensate amplitudes

Must be translationally invariant and real

$$\frac{H_4}{V} = \frac{A}{2}[(|\psi_+|^2)^2 + (|\psi_-|^2)^2] + B|\psi_+|^2|\psi_-|^2 + \frac{C}{2}[|\psi_+|^2(\psi_+\psi_- + \psi_+^*\psi_-^*) + (+\leftrightarrow -)]$$

$$\psi_\pm = \sqrt{n_\pm}e^{i\phi_\pm}$$

$$\frac{H_4}{V} = \frac{A}{2}[n_+^2 + n_-^2] + Bn_+n_- + C\sqrt{n_+n_-}(n_+ + n_-)\cos(\phi_+ + \phi_-)$$

A-interaction of magnons in the same condensate

B-interaction of magnons in different condensates

A<0, B>0

Interaction energy of fourth order in condensate amplitudes

Must be translationally invariant and real

$$\frac{H_4}{V} = \frac{A}{2}[(|\psi_+|^2)^2 + (|\psi_-|^2)^2] + B|\psi_+|^2|\psi_-|^2 + \frac{C}{2}[|\psi_+|^2(\psi_+\psi_- + \psi_+^*\psi_-^*) + (+\leftrightarrow -)]$$

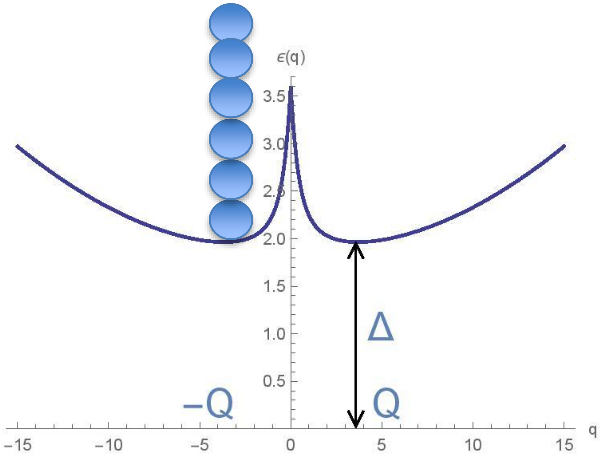
$$\psi_\pm = \sqrt{n_\pm}e^{i\phi_\pm}$$

$$\frac{H_4}{V} = \frac{A}{2}[n_+^2 + n_-^2] + Bn_+n_- + C\sqrt{n_+n_-}(n_+ + n_-)\cos(\phi_+ + \phi_-)$$

A<0, B>0

Configuration with all magnons in one condensate wins

Question: Why the oscillations appear?



$$\frac{H_4}{V} = \frac{A}{2}[n_+^2 + n_-^2] + Bn_+n_- + C\sqrt{n_+n_-}(n_+ + n_-)\cos(\phi_+ + \phi_-)$$

Minimization of energy over $\phi = \phi_+ + \phi_-$

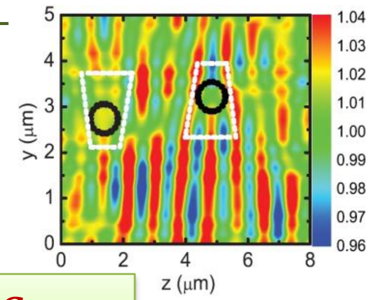
$\phi = 0$ at C<0, D<0

$\phi = \pi$ at C>0, D<0

Phase trapping

$$\frac{H_4}{V} = \frac{A}{2}[n_+^2 + n_-^2] + Bn_+n_- - |C|\sqrt{n_+n_-}(n_+ + n_-)$$

Minimization of energy over n_+, n_- at fixed $n_0 = n_+ + n_-$



Non-symmetric phase $n_+ \neq n_-$ wins in thick films

$$n_\pm = \frac{n_0}{2}\left(1 \pm \sqrt{1 + \frac{C^2}{(B-A)^2}}\right)$$

$$B \gg |A| \gg C$$

Stability problem

Negative interaction energy

$$U = An_0^2\left[1 - \frac{|C|^2}{4(B-A)^2}\right]$$

In thermal equilibrium it would be a collapse

Permanent pumping induces repulsion of magnons

Experimental evidence of repulsion?

Theory of repulsion?

3. Superfluidity of magnon gas. Theory

Chen Sun, T. Nattermann and VP, PRL 2016, J. Phys. D 2017

Condensate + coherence = superfludity, but

Normal liquid (thermal magnons) dominates superfluid more than 100 times

We show that for typical situations the supercurrent is much more than normal one

Principal obstacle: The phase trapping violates conservation of the condensate density and spin current

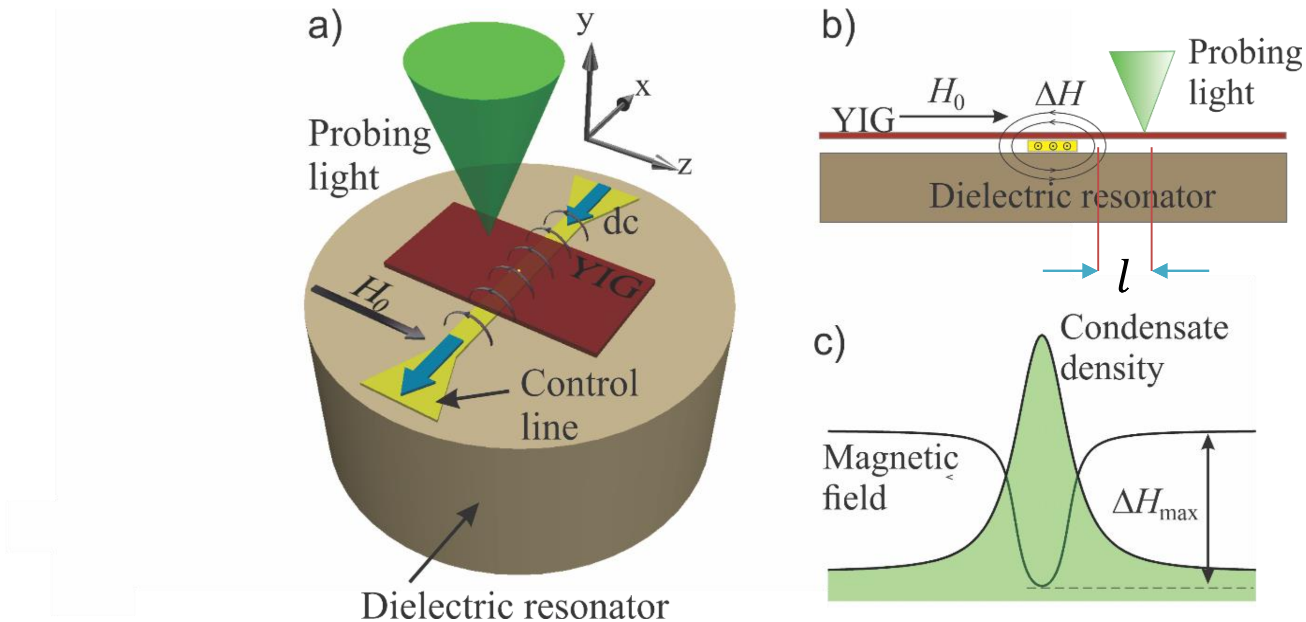
Condensate is not conserved locally, but is conserved globally due to symmetry $\phi \to -\phi$

Spin is transferred to the lattice and returns back since the real reactions are forbidden

4. Experiment with inhomogeneous field

Direct evidence of spatial stability of Bose-Einstein condensate of magnons

I.V. Borisenko[1, 2,*], B. Divinskiy[1], V.E. Demidov[1], G. Li[3], T. Nattermann[4],V.L.Pokrovsky[3,5], and S. O. Demokritov[1]. (Submitted to Nature Communications)

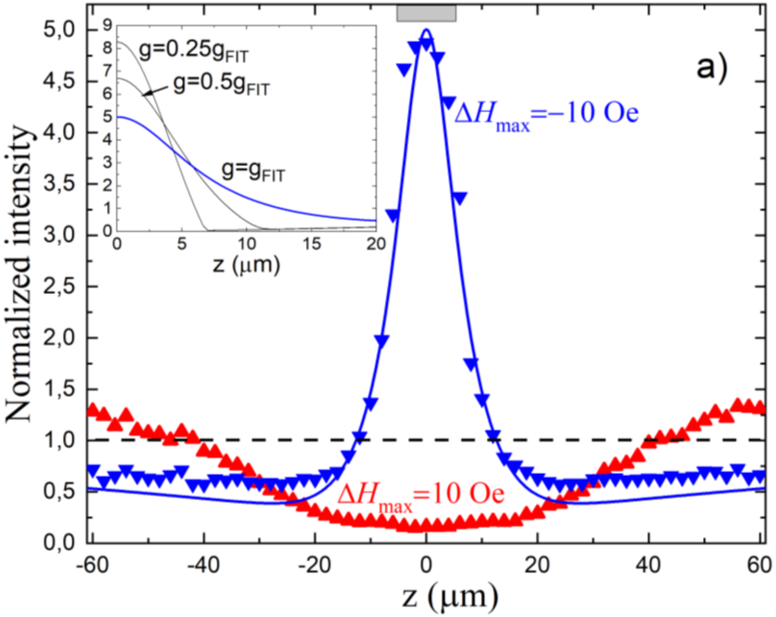


Schematic of the experiment. **a**) General view of the experimental system.

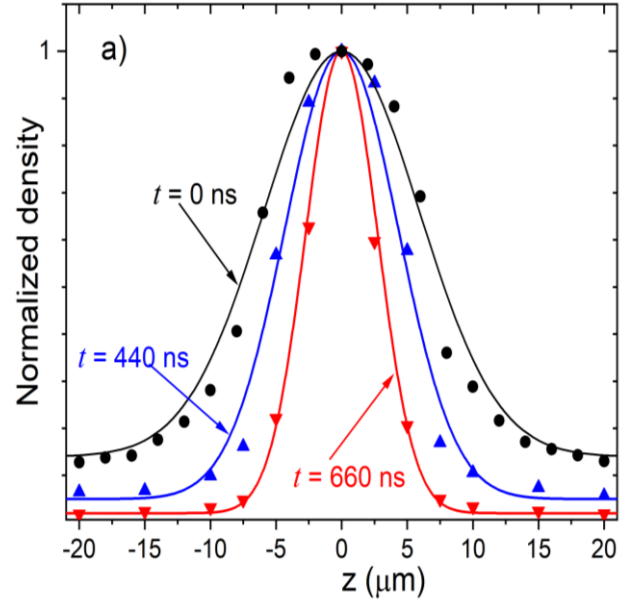
b) Cross-section of the system illustrating the field ΔH created by the control line.

c) Plots of horizontal component of the magnetic field ΔH and the condensate density caused by the inhomogeneity of the field.

Experimental results



Redistribution of the condensate density caused by a potential well and a hill.



Time evolution of the condensate density in potential well after switching the microwave pumping off.

Strong response: change of field 1.6%, change of density about 5 times

Experimental evidence of magnons repulsion

Theoretical model of system with inhomogeneous field

Balance of condensate density: $\frac{\partial n}{\partial t} + \frac{\partial (nv)}{\partial z} = \frac{n_0 - n}{\tau}$

pumping

attenuation

Stationary process: $\frac{d(nv)}{dz} = \frac{n_0 - n}{\tau}$

Dynamics of individual magnon: $m\frac{dv}{dt} + \frac{\partial}{\partial z}(U + gn) = -\frac{v}{\tau}$ $U = -2\mu_B h(z)$

When $n > n_0$ a dissipative current appears: magnons in current acquired velocity $v \sim l/\tau$. Due to collisions they lose their kinetic energy with the rate $\frac{mv^2}{2\tau}$. It produces width of level $\Gamma \sim \frac{mv^2}{2\omega\tau}$, where $\omega = 2\mu_B H/\hbar$.

The number of levels in the potential well of the depth $2\mu_B h$ and the width l is $\sqrt{m\mu_B h}l/(\pi\hbar)$. Average distance between levels $\Delta E = \frac{2\pi\hbar\sqrt{\mu_B h}}{\sqrt{m}l} \ll \Gamma$. This is classical dissipative flow!

Modified continuity equation $\frac{d(nv)}{dz} = \frac{n_0 - n}{\tau}$

Interaction

Dissipative dynamic equation $v = -\eta \frac{dU}{dz}; U = 2\mu_B h + gn$

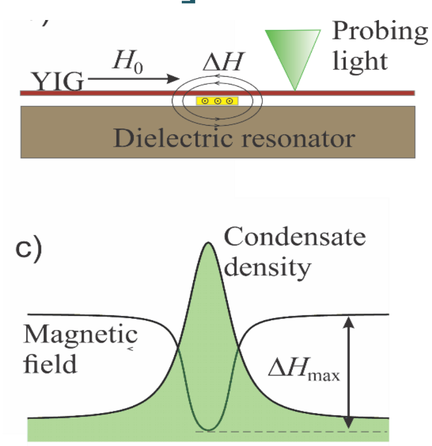
mobility

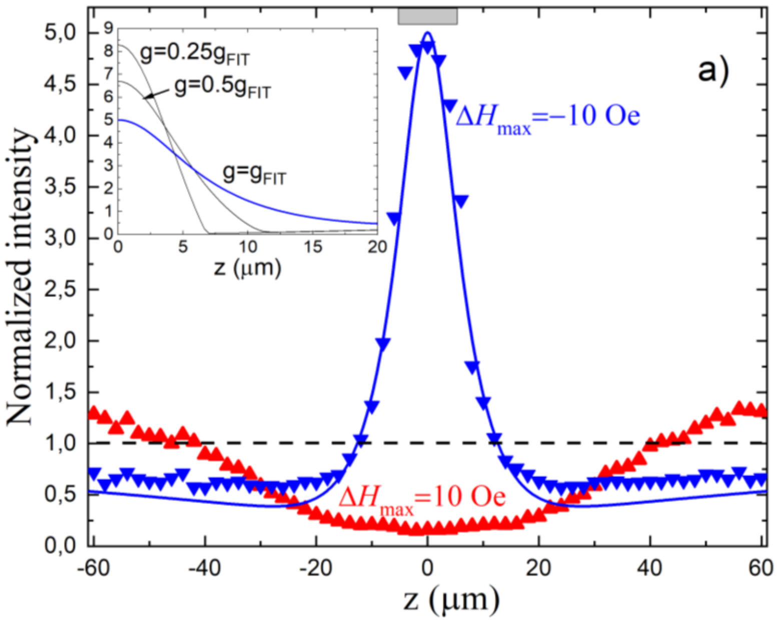
Potential well $h < 0$

After elimination of v: $\eta\tau \frac{d}{dz}\left[n \frac{d}{dz}(2\mu_B h - gn)\right] = n_0 - n$

Boundary conditions

$\frac{dn}{dz} = 0 \text{ at } z = 0; n = n_0 \text{ at } z = \infty$





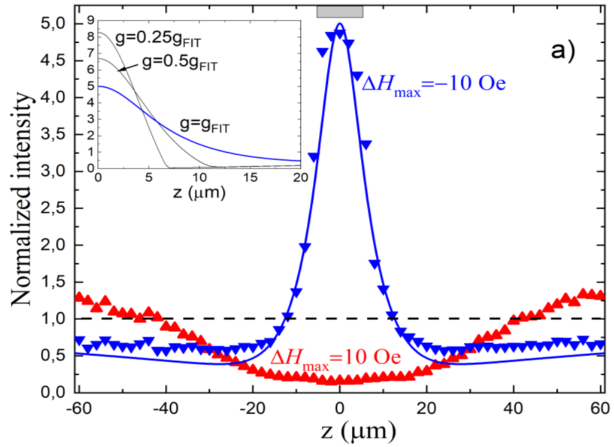
Perfect agreement of numerical calculation and experiment

Fitting parameters: g and η

$g \approx 30\mu_B^2$ - proves stability

Surprising result: extremely high mobility: $\eta = \tilde{\tau}/m \rightarrow \tilde{\tau} \sim 10^{-4} \div 10^{-3} s$

Compare with $\tau \approx 10^{-7} s$ in the middle of density peak



Surprising result: extremely high mobility: $\eta = \tilde{\tau}/m \rightarrow \tilde{\tau} \sim 10^{-4} \div 10^{-3} s$

Explanation: potential well is deep and accumulates many magnons $n_{extra} = 2\mu_B |h|/g$

Extra magnons generate dissipative current $j_{max} \sim n_{extra} l/\tau$

Its compensation proceeds at $n < n_0$ and requires a long distance $L_{rec} > 15l = 150\mu m$

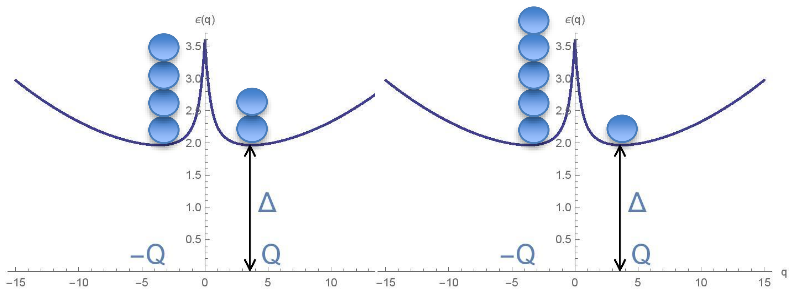
Density of condensate on the tail of the recovery curve becomes very close to n_0

Onset of superfluidity is responsible for large mobility

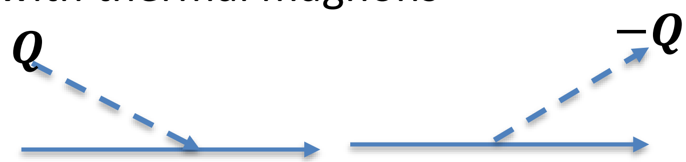
How to resolve discrepancy between LSP theory and experiment?

The state with spontaneously broken symmetry is not realized at room temperature

Relaxation to this process requires non-conservation of momentum



These are long-time Cherenkov processes with thermal magnons



Inter-minima relaxation time is larger than or of the order of the lifetime

Condensate state is symmetric $n_+ = n_- = n/2$

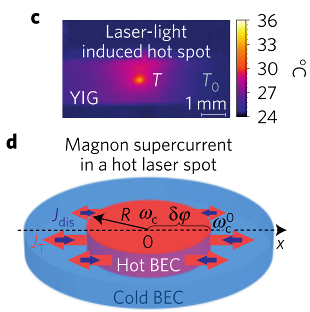
$$H_{int} = \frac{A+B}{4} n^2 \qquad g \approx \frac{B}{2} > 0$$

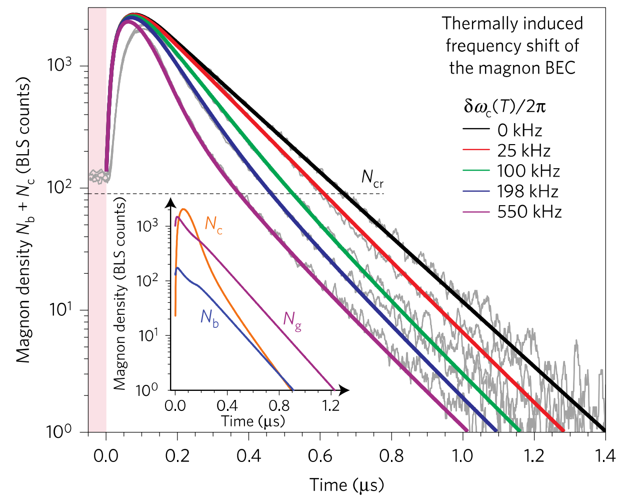
Asymmetric phase with lower energy wins at decreasing temperature.

nature physics
ARTICLES
PUBLISHED ONLINE: 1 AUGUST 2016 | DOI: 10.1038/NPHYS3838

Supercurrent in a room-temperature Bose–Einstein magnon condensate

Dmytro A. Bozhko[1,2], Alexander A. Serga[1], Peter Clausen[1], Vitaliy I. Vasyuchka[1], Frank Heussner[1], Gennadii A. Melkov[3], Anna Pomyalov[4], Victor S. L'vov[4] and Burkard Hillebrands[1*]





Laser creates hot point in the center of sample.

Theoretical curves of the condensate decay vs. experimental measurements.

Agreement requires inclusion of potential flow $\boldsymbol{j} = n\nabla\phi$

Super-heat-conductivity?

Weak point: potential flow is possible in normal liquid.

Assume that the condensate is symmetric $n_+ = n_- = n/2$

$$U_{int} = \frac{(B + A)n^2}{4} > 0$$

5. Conclusions

- Experiment shows that there is repulsion between condensate magnons in the regime of permanent pumping. No instability.
- It shows that the appearance of over-equilibrium condensate leads to dissipative currents that destroy coherence.
- Relaxation to the quasi-equilibrium state proceeds on large distance.
- Fitting of the experimental distribution of density to simple theoretical model displays very large mobility on the tale of the distribution. It can be treated as onset of superfluidity.
- Experiment of the Hillebrands group displays indirect evidence of superfluid convective heat conductivity.
- Theory explains the repulsive interaction of magnons by assumption that there is no spontaneous violation of reflection symmetry at room temperature.

Modified Hydrodynamic equations for stationary flow

$$\nabla \boldsymbol{j} = \frac{n_0 - n}{\tau}$$

$$\frac{\partial \Pi_{ik}}{\partial x_k} + \frac{n}{m}\frac{\partial U}{\partial x_i} = -\frac{j_i}{\tau}; \ \Pi_{ik} = n v_i v_k + \delta_{ik}\frac{P}{m}$$

$$P = \frac{g n^2}{2}; U = 2\mu_B h + u(n_{extra})$$

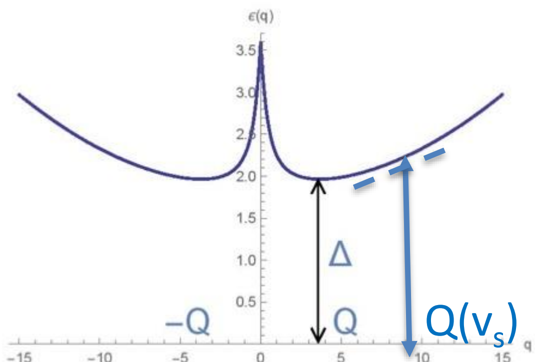
$$h(z) = -\frac{2I}{cl}\left(\arctan\frac{l + d + 2x_0}{d + 2x_0} - \arctan\frac{l - d - 2x_0}{d + 2x_0}\right)$$

What superfluidity means in a dissipative system?

Similarity to a laser: pumping is necessary. Difference: closeness to the ground state

Landau criterion of superfluidity: excitations appear at a finite velocity of condensate

Define $Q(v_s)$ by the requirement $\left.\frac{\partial \varepsilon}{\partial k}\right|_{k=Q(v_v)} = v_s$



Energy-momentum conservation at decay: $\varepsilon\big(Q(v_s)\big) = \varepsilon(k) + \varepsilon(Q(v_s) - k)$

$$v_s > v_{sc} = 2\sqrt{D\gamma H}/\hbar \approx 0.5km/s$$

Drift velocity of thermal magnons in the gradient of field 1T/μm is 1mm/s

Complimentary material

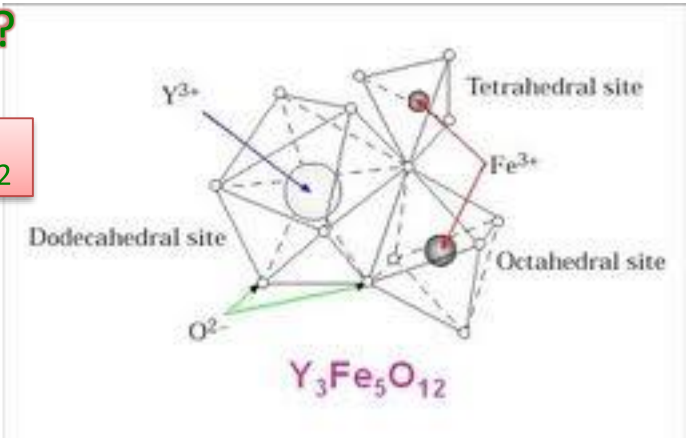
1. Magnons in YIG?

YIG crystal

Chemical formula: $Y_3Fe_5O_{12}$

Crystal structure

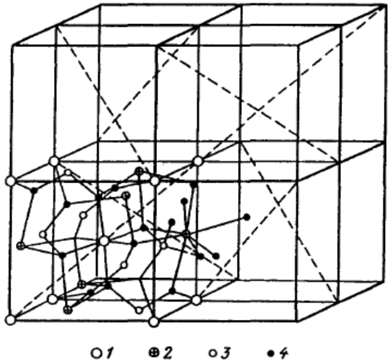
a=1.2 nm



80 atoms in elementary cell

Magnetic properties: Ferrite T_c=560K

S_{cell}=14.5



Electric properties: Insulator

Magnons almost do not attenuate

20 spin-wave branches in the bulk