LECTURE 9

Magnon condensation

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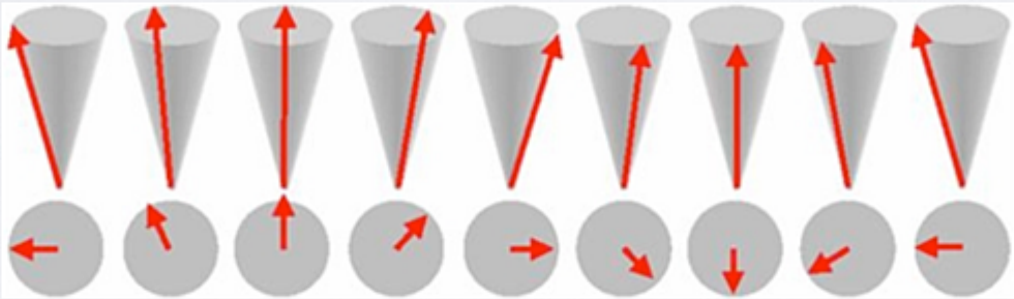
Magnon condensation
definition

Existence of magnons predicted by F. Bloch in 1929

Magnons are elementary particles of a spin-wave.

They are collective excitations of the electron spin system in ferromagnetic metals and insulators.
A disturbance in local magnetic ordering can propagate in a magnetic material in the form of a wave.

one complete precession distributed over a chain of spins



magnetic moments

Wave of deflected magnetic moments propagate through the crystal

images: Patryk Nowik-Boltyk, Westfalische Wilhelms-Universitat Munster

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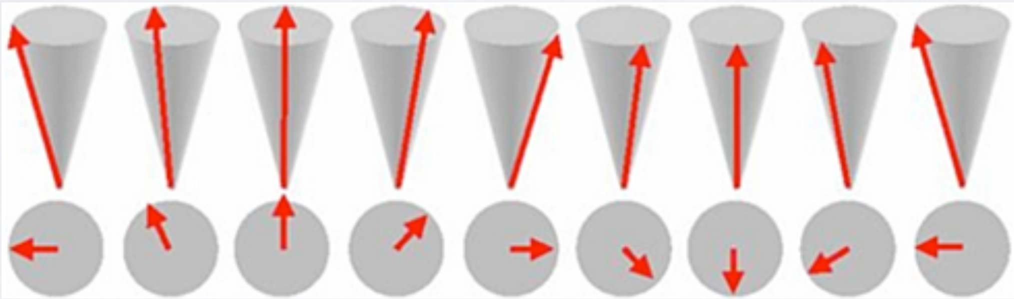

magnetic moments

Wave of deflected magnetic moments propagate through the crystal

Deflected spins precess about the direction of external magnetic field.

Precession is transferred to vibration of atoms. Decay of the spin-waves is perceived as a heat.

images: Patryk Nowik-Boltyk, Westfalische Wilhelms-Universitat Munster

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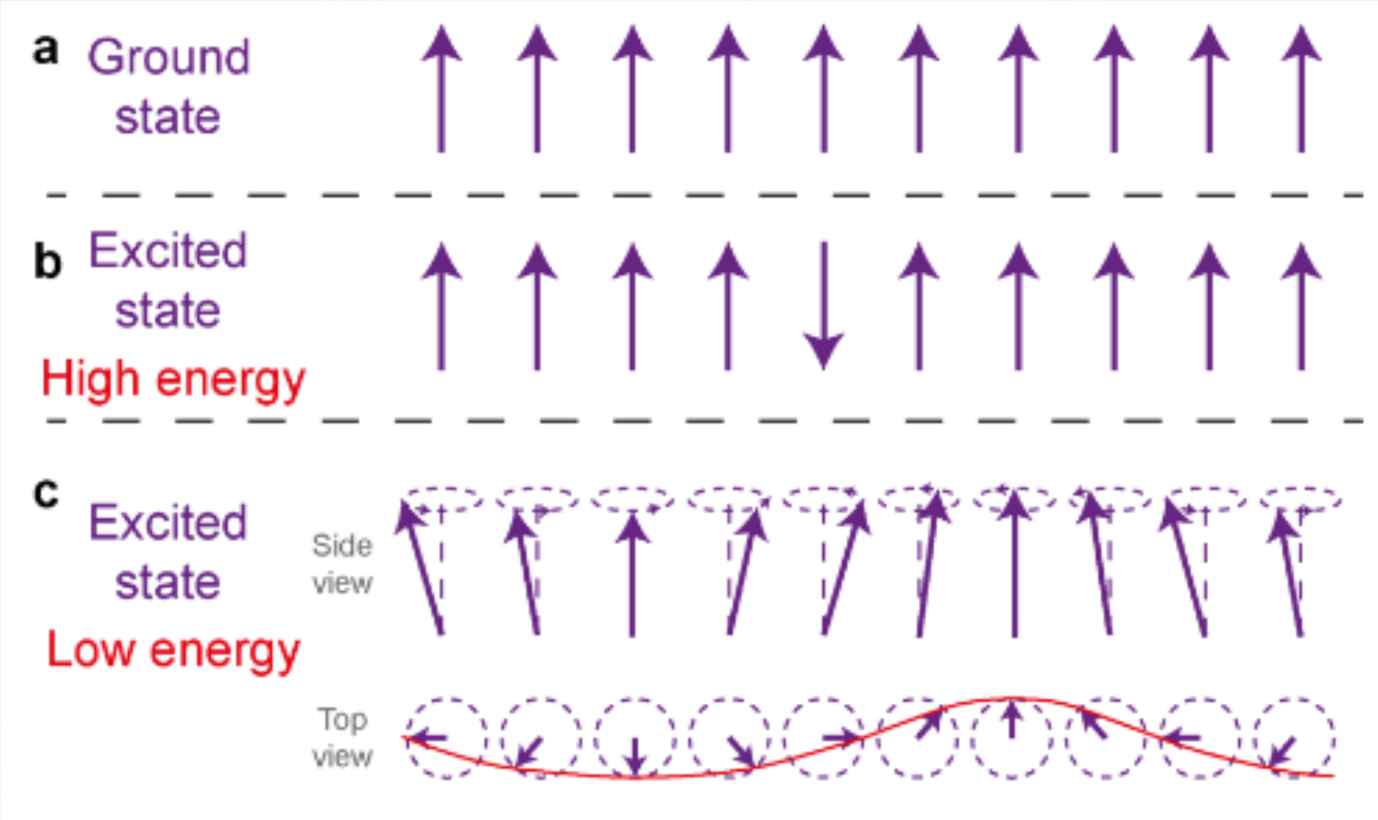


Simple picture of a ferromagnet.
(a) Ground state of the magnet: All spin are aligned.
(b) Excited state of the magnet: one spin is flipped.
(c) Magnon excited state with a lower energy than in (b): Instead of flipping one spin, the net spin reduction is distributed over the whole system. The spins are rotating (precessing) around their equilibrium, forming a **magnon**.

Magnon spintronics, Zernike et al. Univ. of Groningen

Magnon condensation
definition

Wave of deflected magnetic moments propagate through the crystal

wave - particle (quasi-particle) duality

MAGNONS

They carry energy

$$E = h\nu$$

precession frequency
of the individual spins
in a spin wave

The velocity of magnons depends on the angle between propagation direction and external magnetic field and on precession frequencies of the individual spins building up the magnon.

Examples:
polycrystalline metallic films of Permalloy (Py, $Ni_{81}Fe_{19}$)
single-crystal films of yttrium–iron–garnet (YIG, $Y_3Fe_5O_{12}$)

Magnon condensation

Bose - Einstein condensation

They are integer spin quasiparticles, which act as bosons

! important: number of magnons is not conserved !

- due to short lifetime
- it is easy to create them (~µeV)

Necessary conditions for magnon BEC

the lifetime of magnons must be much longer than the relaxation time

microseconds time scale

nanoseconds time scale

The main mechanism of magnon thermalization is four-magnon scattering, which corresponds to particle–particle collision processes

The chemical potential of a magnon gas in thermodynamic equilibrium with the lattice is zero, as the number of magnons is not conserved, mainly owing to the energy exchange between the magnons and the lattice.

Magnon condensation

example

Patryk Nowik-Boltyk, Westfalische Wilhelms-Universitat Munster and O. Dzyapko et al., New Journal of Physics, Volume 9, March 2007

Yttrium Iron Garnet (YIG): $Y_3Fe_2(FeO_3)_3$

a thin (~5μm) ferromagnetic and electrically isolating crystal placed in a magnetic field

Creation of magnons:

spin lattice will follow external magnetic field

spin waves in YIG-film have frequencies ~ GHz

alternating magnetic field with GHz frequency

microwaves

Destruction of magnons:

excitation is transferred to atomic lattice through vibrations

vibrations are dissipated as a heat

microseconds time scale

Magnon condensation

example

Patryk Nowik-Boltyk, Westfalische Wilhelms-Universitat Munster and O. Dzyapko et al., New Journal of Physics, Volume 9, March 2007

Thermal distribution of magnon gas:

magnons scatter to distribute the kinetic energy over the whole gas

number of scattering events depends on magnon density

at high magnon densities the „thermalization" time is of nanoseconds

thermal energy distribution

Magnon gas is in quasi-equilibrium.

Constant microwave field is maintaing magnons in quasi-equilibrium.

Magnon condensation

signatures of mBEC

thermalization process starts

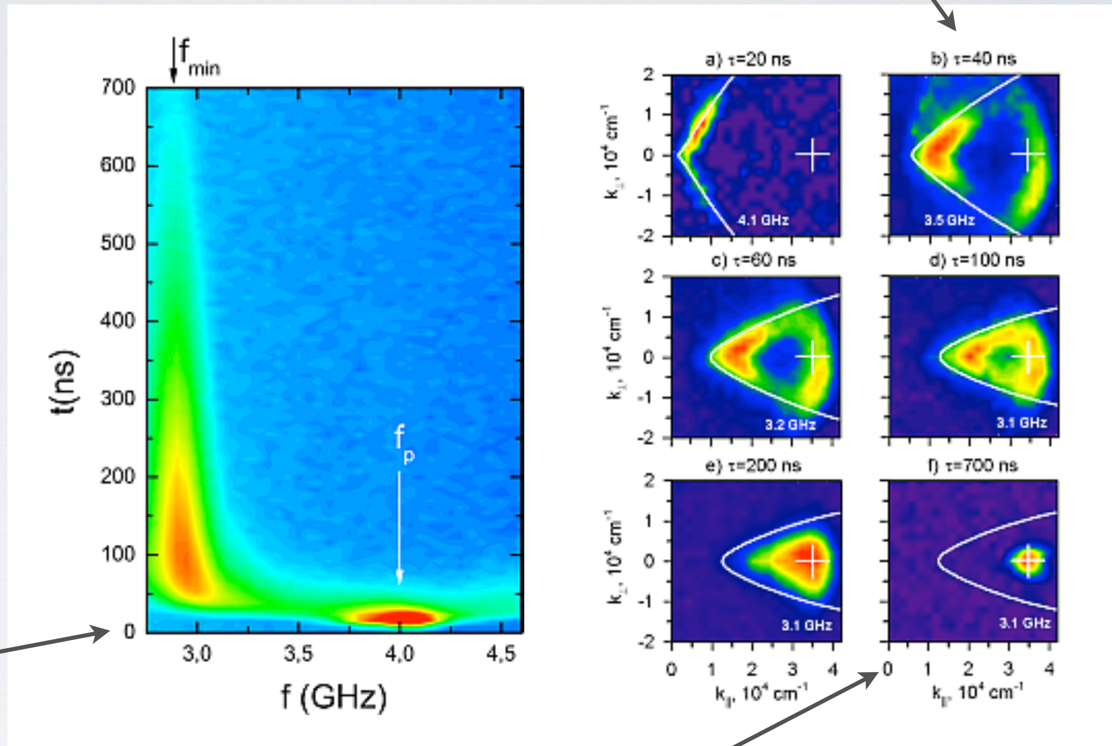
mBEC in quasi-equilibrium

Over long time magnons occupy lowest energy state of 2.9 GHz (depends on external magnetic field)

Magnons scatter and lower their energy

Magnons are created at high density at 4GHz

At t=0, GHz pulse creates population of magnons



k perpendicular to external magnetic field

f ~ magnon energy

k parallel to external magnetic field

mBEC - accumulation of magnons with narrow wavevector distribution

k ~ magnon wavelength and propagation direction

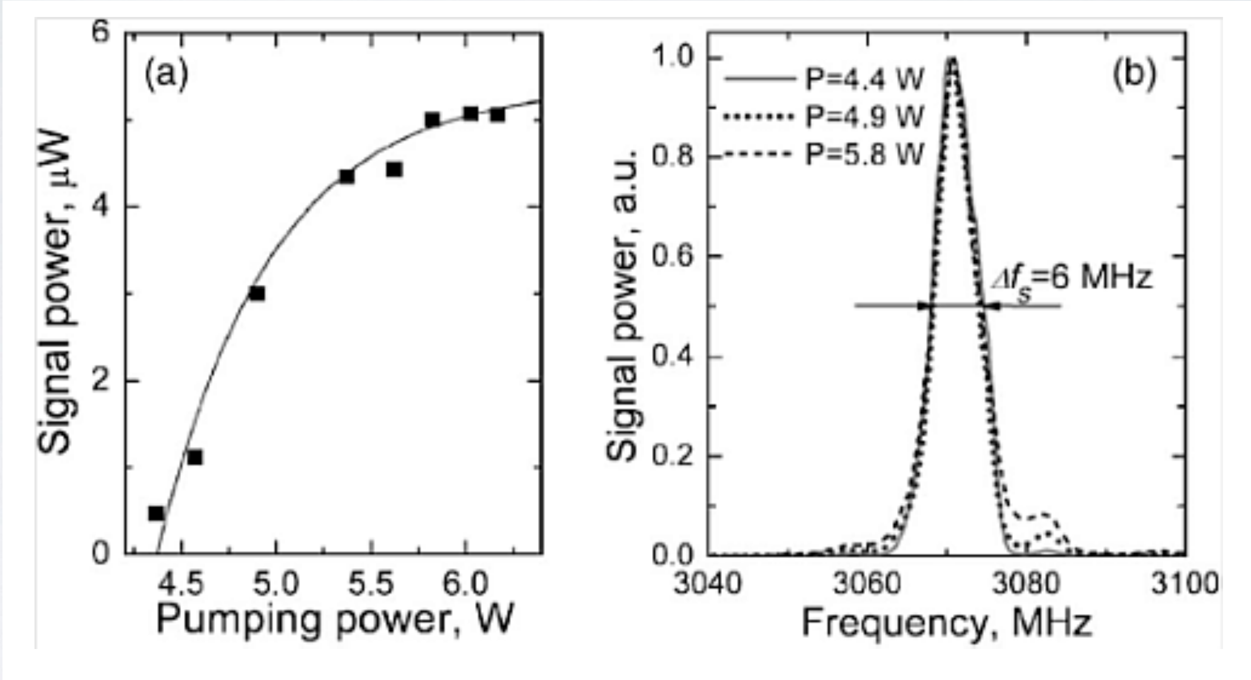
images: Patryk Nowik-Boltyk, Westfalische Wilhelms-Universitat Munster

Magnon condensation

coherence of mBEC

Precession of two spins belonging to different magnons must not be connected to each other, but:

- the magnons in a BEC are not individual anymore
- their precessions are synchronized
- spins from different magnons in a condensate precess parallel to each other



The alternating magnetic fields originating from the precessing spins interfere constructively and we get an alternating magnetic field with large amplitude and with the same frequency as the precession frequency of the spins.

coherent precession is inducing macroscopic polarization

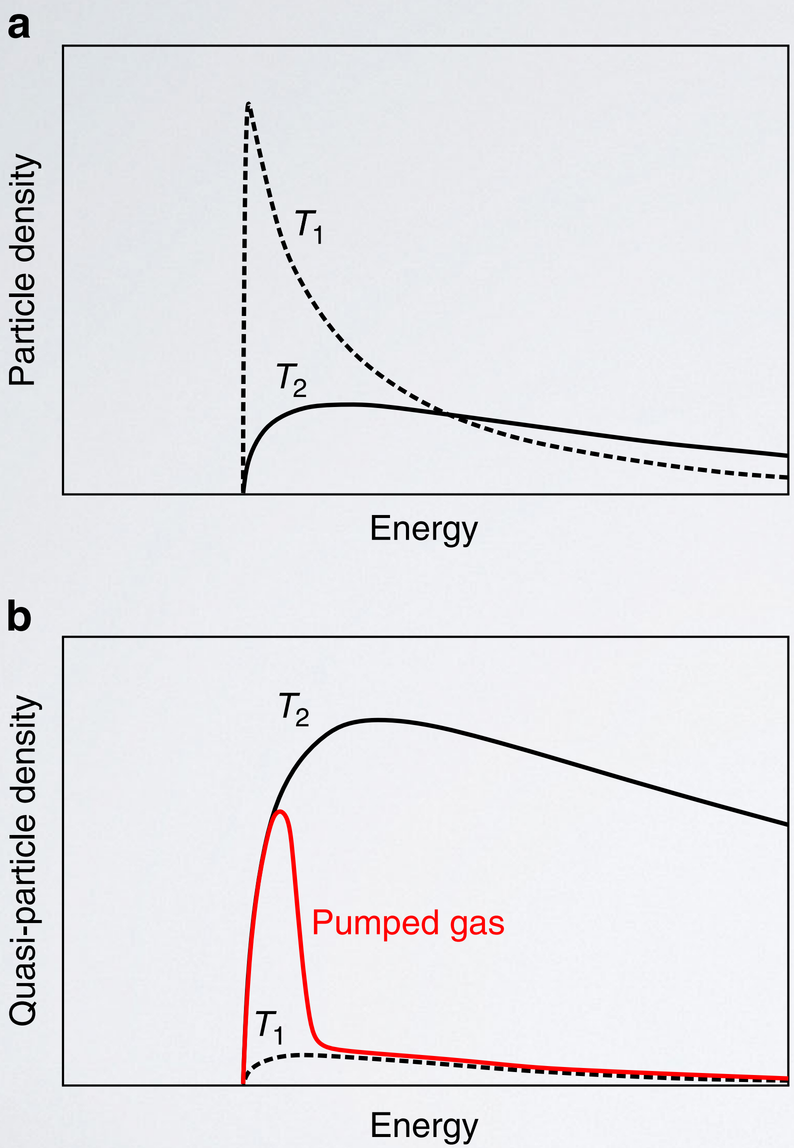
Precessing spins create a strong electromagnetic wave at microwave frequencies.

images: Patryk Nowik-Boltyk, Westfalische Wilhelms-Universitat Munster

Magnon condensation

Non-equilibrium condensate

T1<T2



Equilibrium system

Non-equilibrium system

A. A. Serga, et al. Nature Commun. 5, 3452 (2014).

Magnon condensation

Non-equilibrium condensate

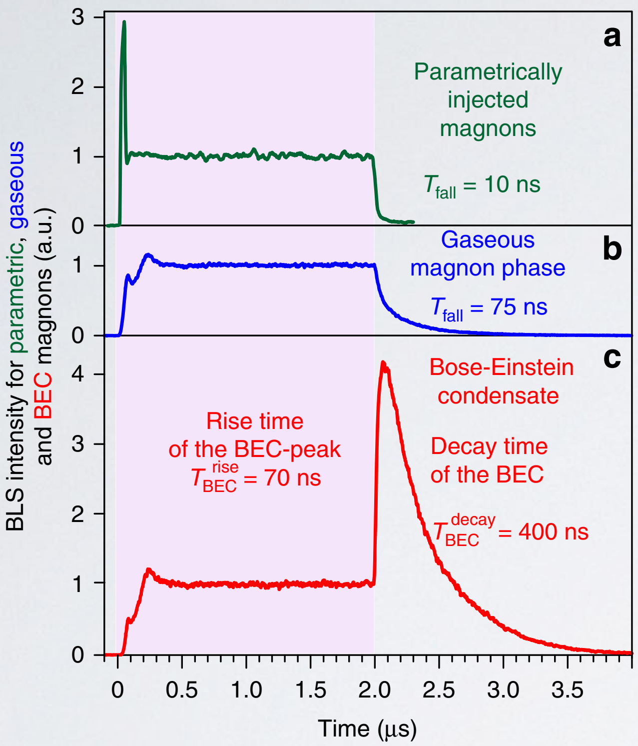
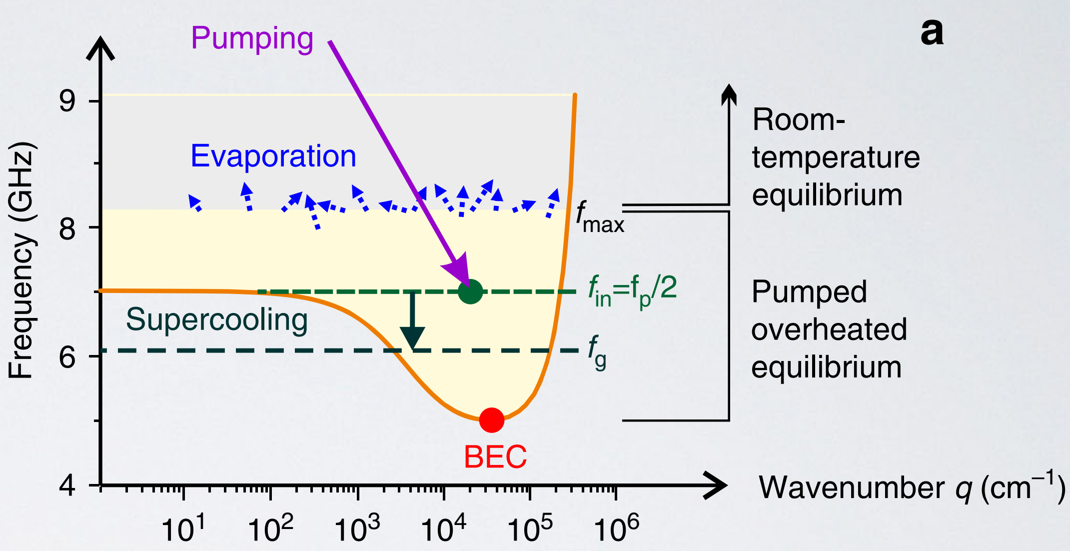


Figure 3 | Time evolution of the magnon density. The BLS intensity is proportional to the magnon density. BLS measurements were performed in frequency windows of 150 MHz around 7, 6 and 5 GHz. The purple area indicates the time over which the pump is active. (**a**) Parametrically injected magnons at 7 GHz. The sharp peak at the front of the pulse is due to transient processes in the system of parametrically excited magnons[21,25]. (**b**) Gaseous magnon phase lying between the region of parametrically injected magnons and the bottom of the magnon spectrum (6 GHz). (**c**) BEC at the bottom of the magnon spectrum (5 GHz). The decay of the parametrically injected (primary) and gaseous magnons after the end of the pumping pulse is non-exponential. The indicated fall times correspond to 50% decay. Note that the rise time of the dramatic jump in the density of the condensed magnons is well correlated with the decay of the gaseous magnons.



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Magnon spintronics = magnonics

Magnon spintronics is the field of spintronics concerned with structures, devices and circuits that use spin currents carried by magnons.

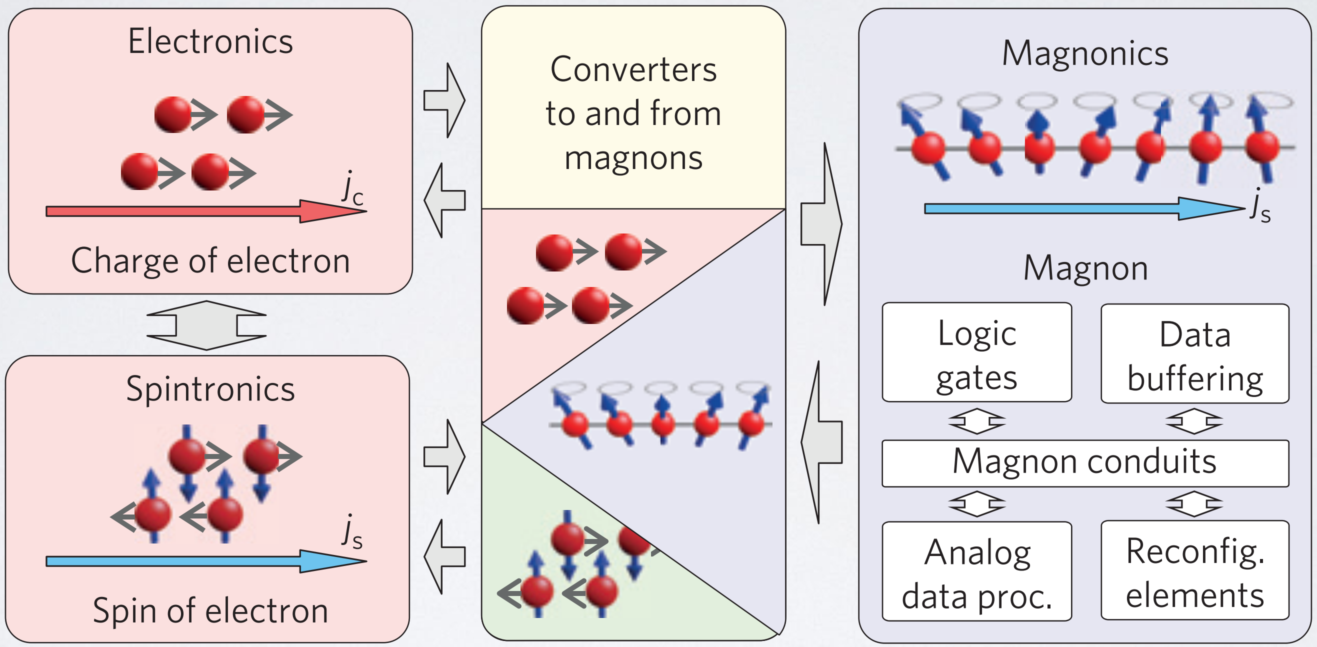

Figure 1 | The concept of magnon spintronics. Information coded into charge or spin currents is converted into magnon currents, processed within the magnonic system and converted back[47].

A. V. Chumak et al., Magnon spintronics, Nature Physics 11(6) 2015

Magnon spintronics = magnonics

Conversion of magnon currents into electron currents: strip antenna or a coplanar antenna, in which spin waves induce an a.c. current /magnetization precession in a magnetic film will generate a spin-polarized electric current in an attached non-magnetic metallic layer

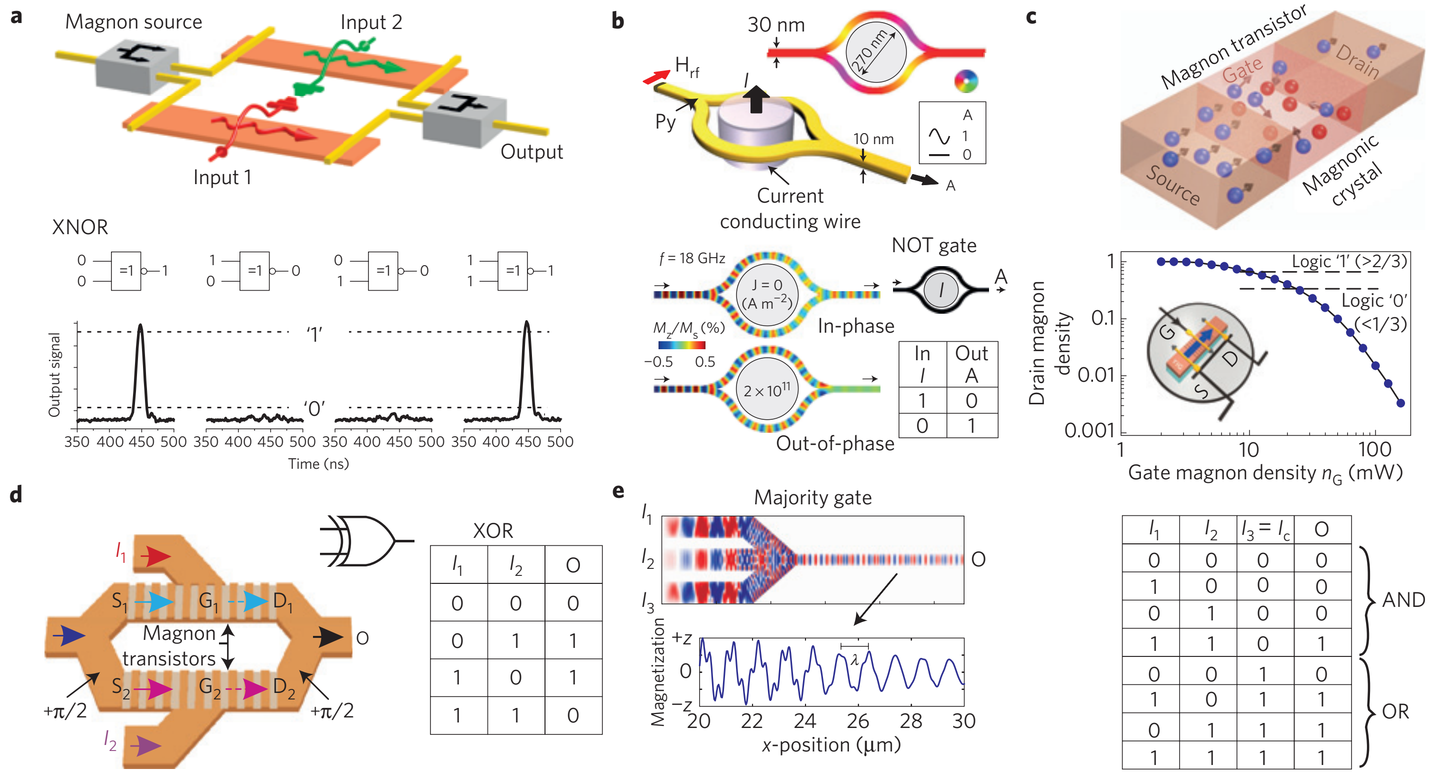

Figure 4 | Magnon-based processing of binary data. **a**, Spin-wave XNOR logic gate based on a Mach–Zehnder interferometer with electric current-controlled phase shifters[10,47]. The bottom panel shows the output pulsed spin-wave signals measured for different combinations of the input d.c. signals. **b**, Nanosized Mach–Zehnder spin-wave interferometer designed in the form of a bifurcated Py conduit girdling a vertical conducting wire (adapted from ref. 11). The simulation of a NOT logic operation is shown below for two different d.c. currents, which correspond to the logic '0' and '1' inputs, respectively. **c**, Operational principle of a magnon transistor[7]: the source-to-drain magnon current (blue spheres) is nonlinearly scattered by gate magnons (red spheres) injected into the gate region. The spatial localization and, as a consequence, a high density of the gate magnons is provided by a magnonic crystal. The measured drain magnon density is presented in the bottom panel. **d**, All-magnon chip proposed for XOR logic operation. The magnon densities sent to the transistor sources S_1 and S_2 are controlled by the input magnon signals I_1 and I_2 applied to the gates zG_1 and G_2. In the case when both input signals are '0', the output signal is also '0' owing to destructive interference. The application of the magnon signal to only one of the gates switches off one of the source-to-drain currents and results in the '1' output. Finally, switching off both currents results in the output '0'—see the truth table. **e**, Majority gate operating with data coded into the spin-wave phase[17]. The colour map represents the spin-wave amplitude for the case of equal input phases. The majority gate can perform OR and AND logic operations (also NOR and NAND if the read-out position is shifted by $\lambda/2$) if one of its inputs is used as a control input I_C—see the truth table.

Magnon condensation

further reading

MAGNON BOSE EINSTEIN CONDENSATION, Patryk Nowik-Boltyk, https://www.uni-muenster.de/Physik.AP/Demokritov/

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

S. O. Demokritov et al., Nature 443, 430-433 (28 September 2006)

Direct observation of Bose–Einstein condensation in a parametrically driven gas of magnons

O Dzyapko et al., New Journal of Physics, Volume 9, March 2007

A. A. Serga, et al. Bose–Einstein condensation in an ultra-hot gas of pumped magnons. Nature Commun. 5, 3452 (2014).