BEC of magnons in superfluid 3He-B as a quantum resonant amplifier

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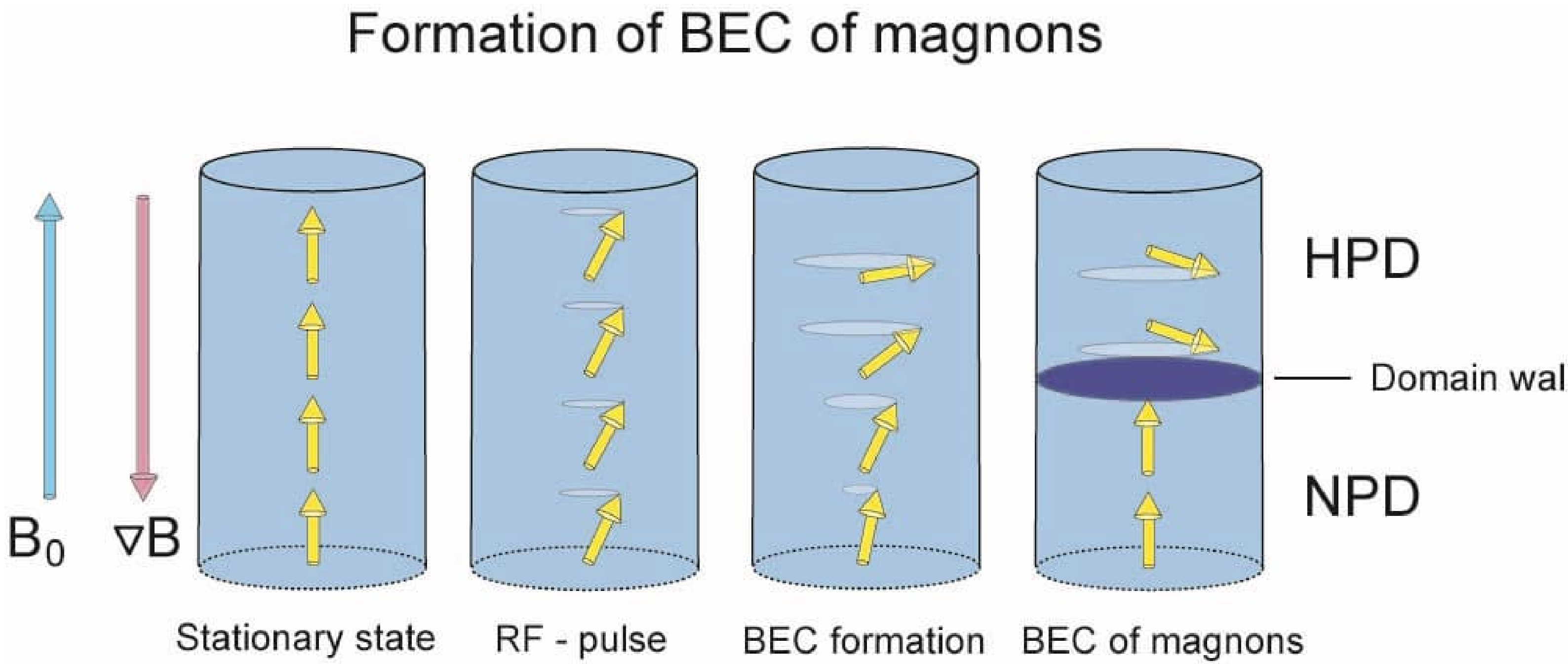
Talk outline:

❑ Extremely short introduction to BEC of magnons in 3He-B

❑ Goldstone/non-Goldstone oscillation modes of the HPD

❑ Non-Goldstone oscillation mode of HPD as quantum resonant amplifier

❑ Conclusion



Spontaneous generation → B-E condensation, evidence for spin superfluidity

Wave function:

spin part

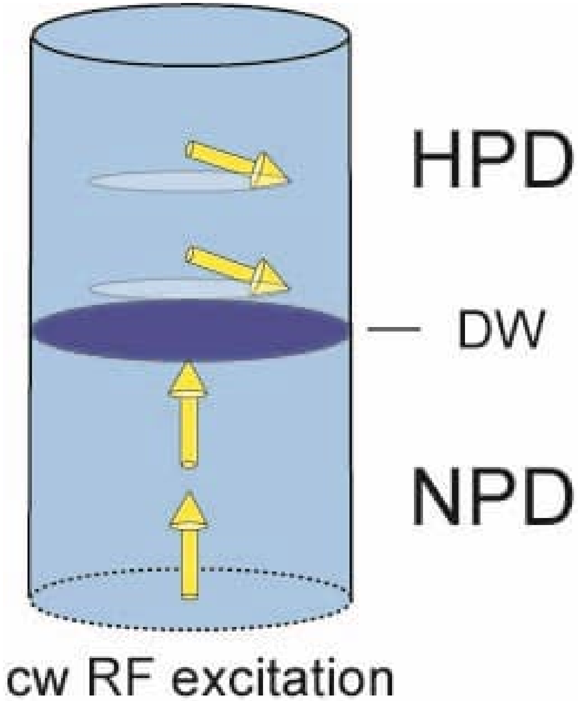
$$\Psi = \Psi_L(\vec{k})\Psi_S(\vec{k}) \longrightarrow \Psi_S = \left|\Psi_{S0}\right|.e^{i\alpha}$$

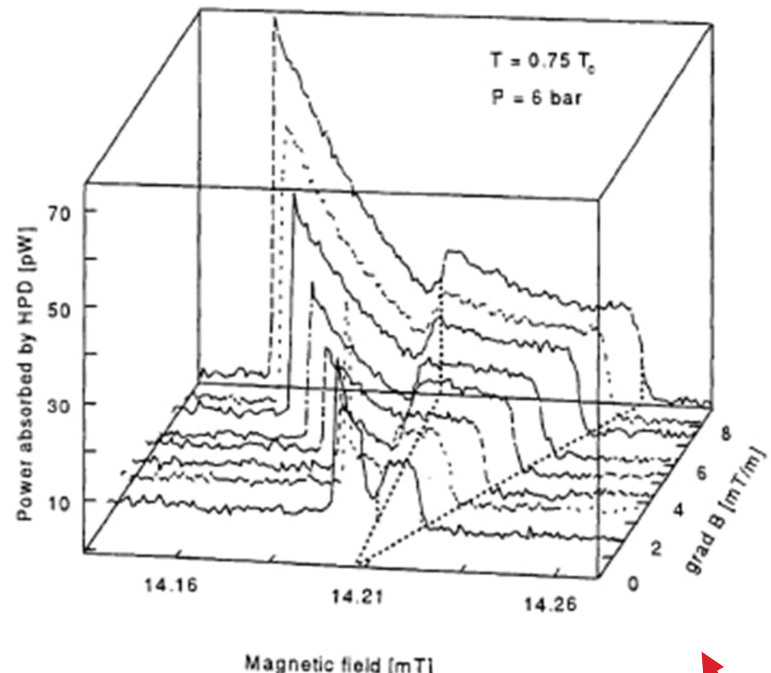
α – is the phase of spin precession $\nabla\alpha \neq 0 \rightarrow currents$

HPD discovered by: A.S. Borovik-Romanov et al. JETP Lett. 40, 1033 (1984)

Coherently spin precessing states – evidence of BEC of magnons

cw – NMR method





Energy dissipation due to presence of quasiparticle excitations.

cw – NMR method compensates energy losses due to dissipation, the HPD can be continuously maintained.

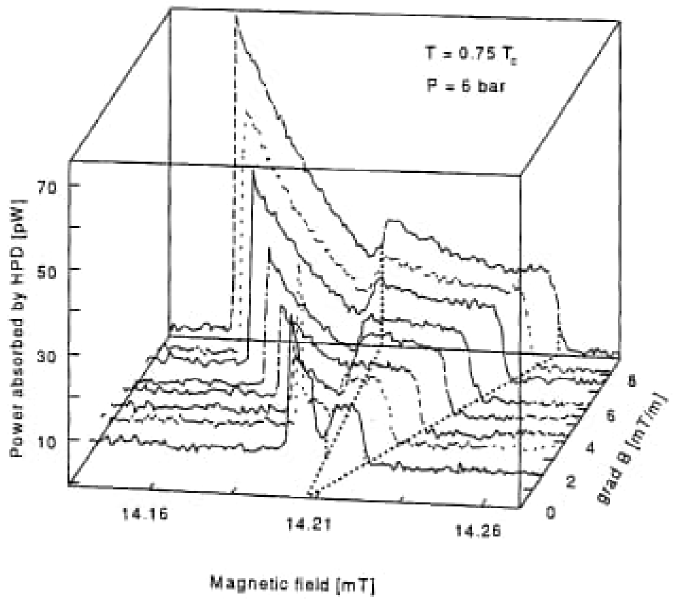
Larmor resonance condition →

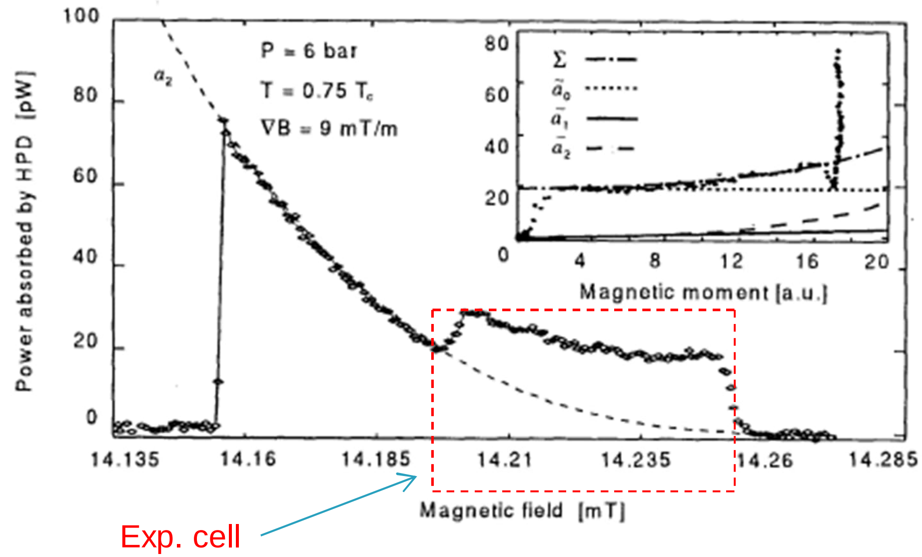
$$\omega_L = \gamma(B_0 + \nabla B.z)$$

Processes of magnetic relaxation in superfluid 3He-B

HPD – as an experimental toll used for study of MRP (zero spin current).

The presence of quasiparticle excitations leads to energy dissipation





Processes of magnetic relaxation: spin diffusion, surface relaxation and L-T relaxation

Hydrodynamic condition

$$\omega_L \tau << 1$$

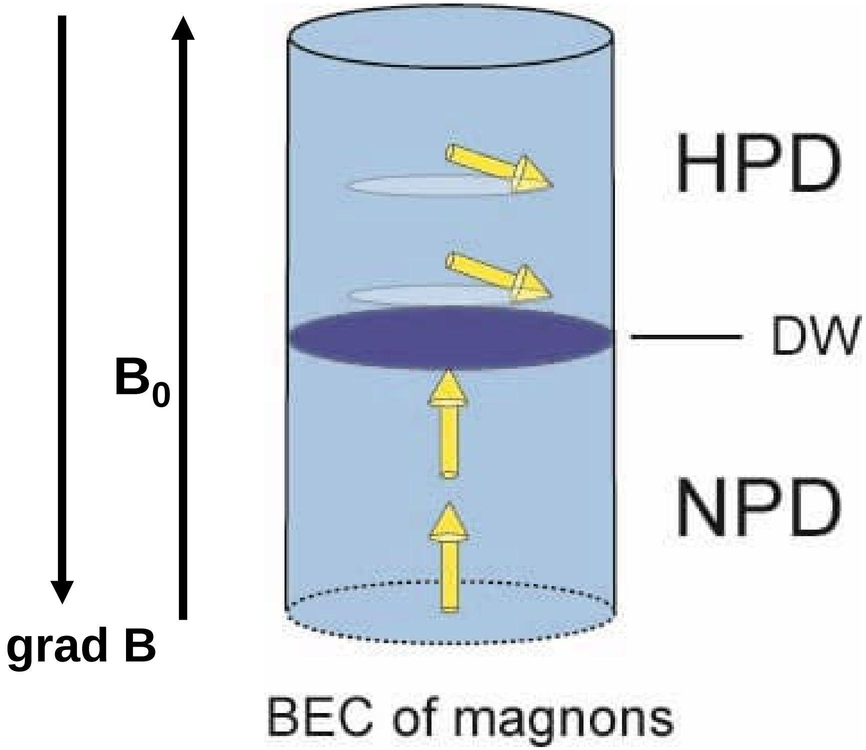
$$\dot{Q} = \sigma \frac{\chi(T)}{\gamma^2} \frac{D_\perp \omega_L^2}{\lambda_F} .S + 2\pi w_s R.L + \frac{5}{16} \chi(T) \tau_R S \frac{\omega_L^2 (\nabla\omega)^2}{\gamma^2} .L^3$$

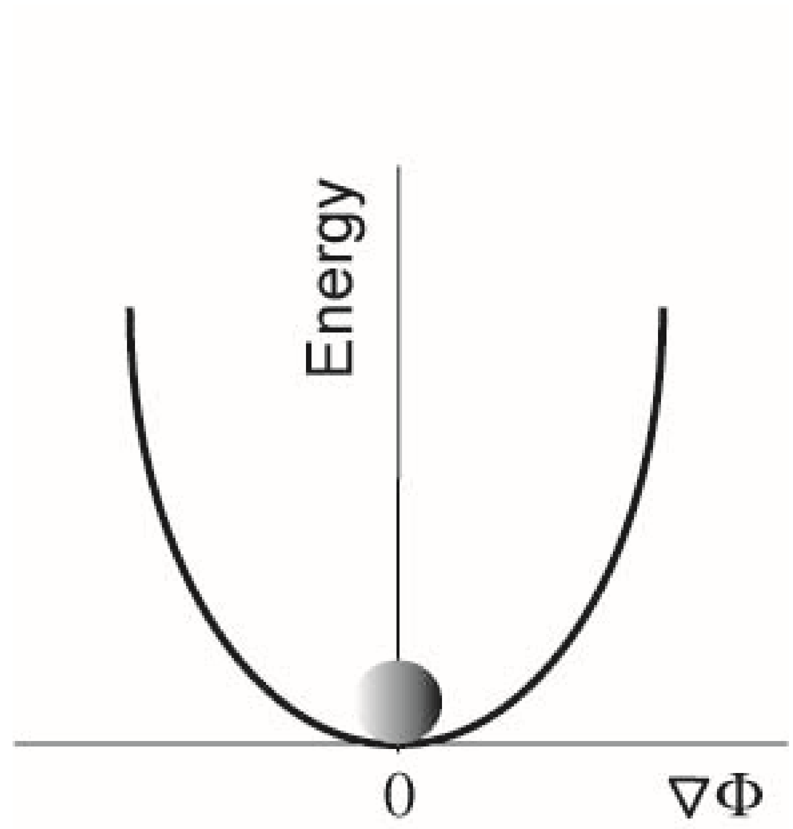
Domain wall thickness

$$\lambda_F = \left(\frac{c_{II}^2}{\nabla\omega.\omega} \right)^{1/3}$$

$$\dot{Q} = a_0(T, \nabla\omega^{1/3}) + a_1(T).L + a_2(T, \nabla\omega^2).L^3$$

Coherently spin precessing states – evidence of BEC of magnons



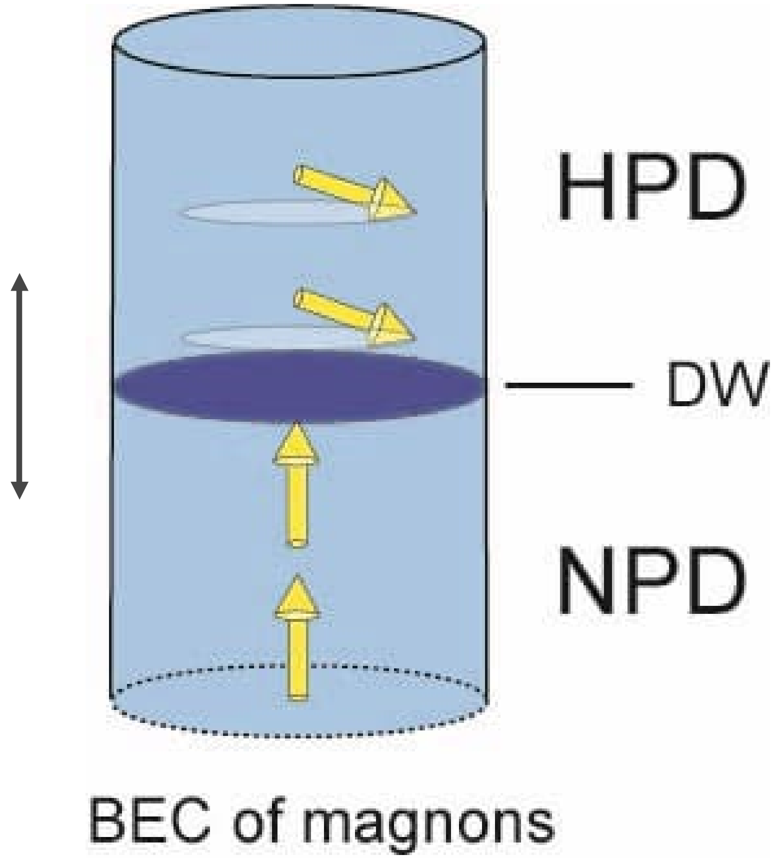


Dynamical equilibrium state state, state of minimum energy.

Rotating frame of reference ($B_{eff}(z)=0$).

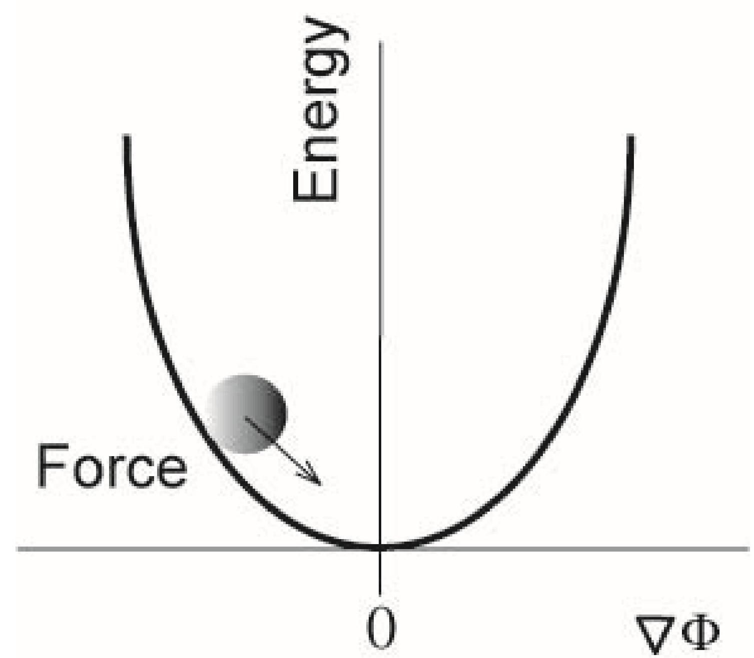
$$\Psi_S = \left|\Psi_{S0}\right| . e^{i\Phi}$$

Coherently spin precessing states – evidence of BEC of magnons



Perturbation – additional field

$$\nabla\Phi \neq 0 \rightarrow currents$$

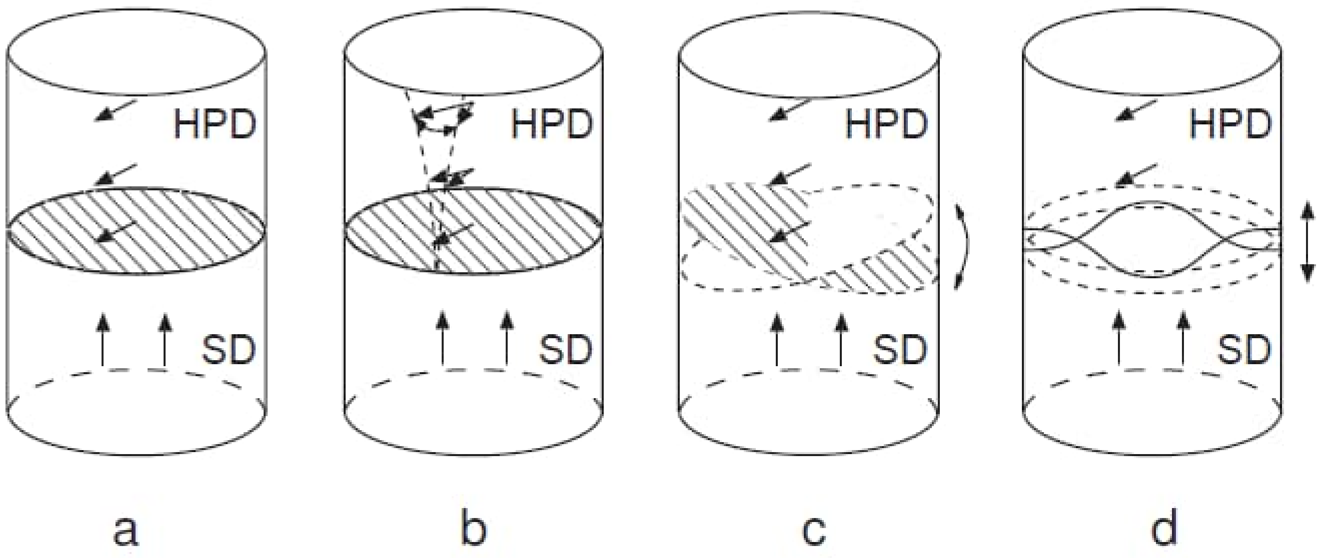


Deflection from energy minimum

Oscillations around minimum
Goldstone (phonon) mode

Goldstone mode of BEC of Magnons in 3He-B

Deflection of the HPD from ground state may lead to generation of the Goldstone (gapless) collective oscillation modes:



Schematic visual representation of the HPD–SD oscillation modes:
HPD stationary state (a),
torsion mode (b), planar mode (c) and first axial mode (d)

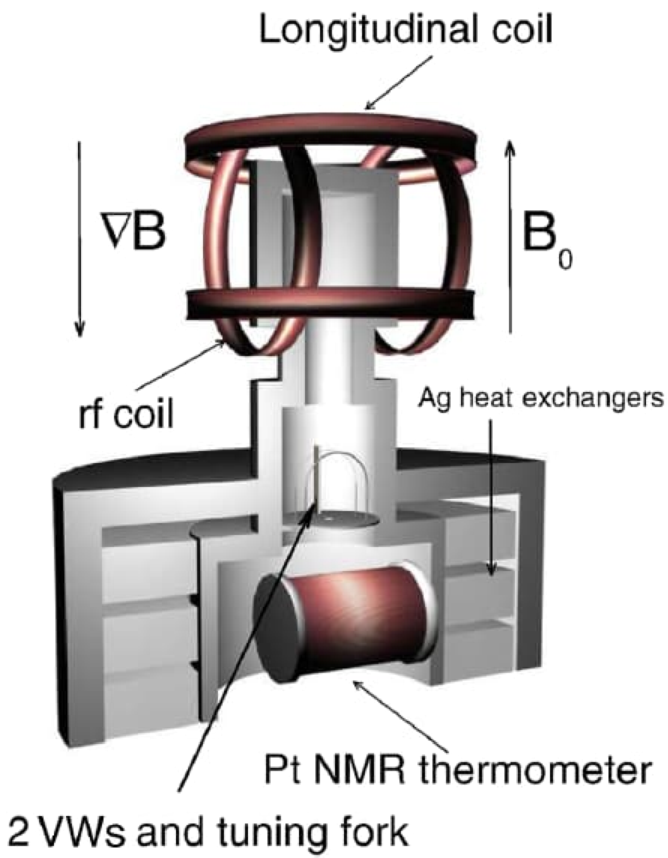
Yu.M. Bunkov et al., JETP Lett. 43, 168 (1986)

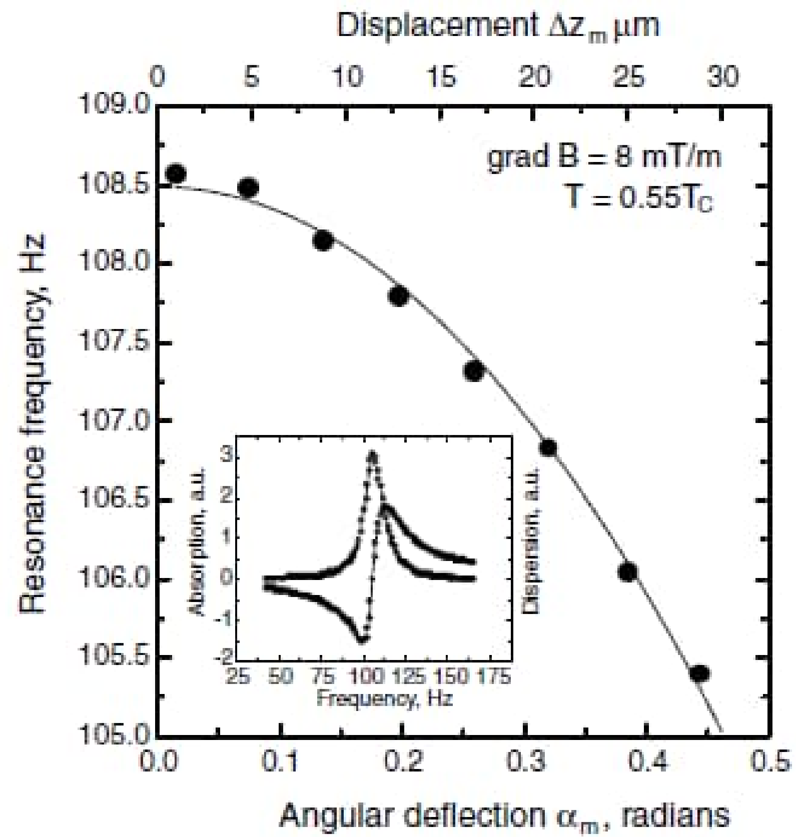
Yu.M. Bunkov et al., Physica 178B 196 (1992)

I.A. Fomin, JETP Lett. 43 171 (1986)

E. Gažo, et al., PRL. 91 55301 (2003)

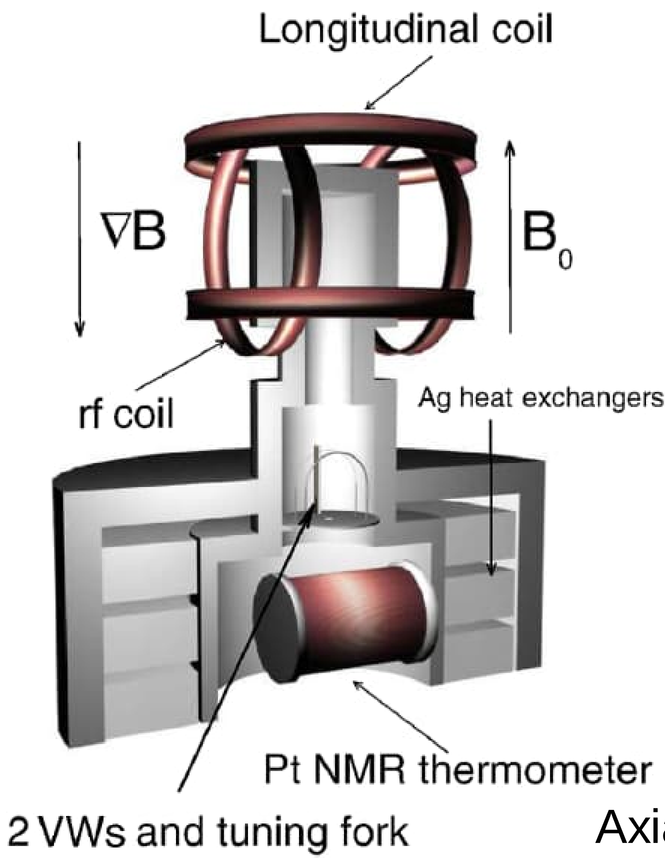
Goldstone mode of BEC of Magnons in 3He-B

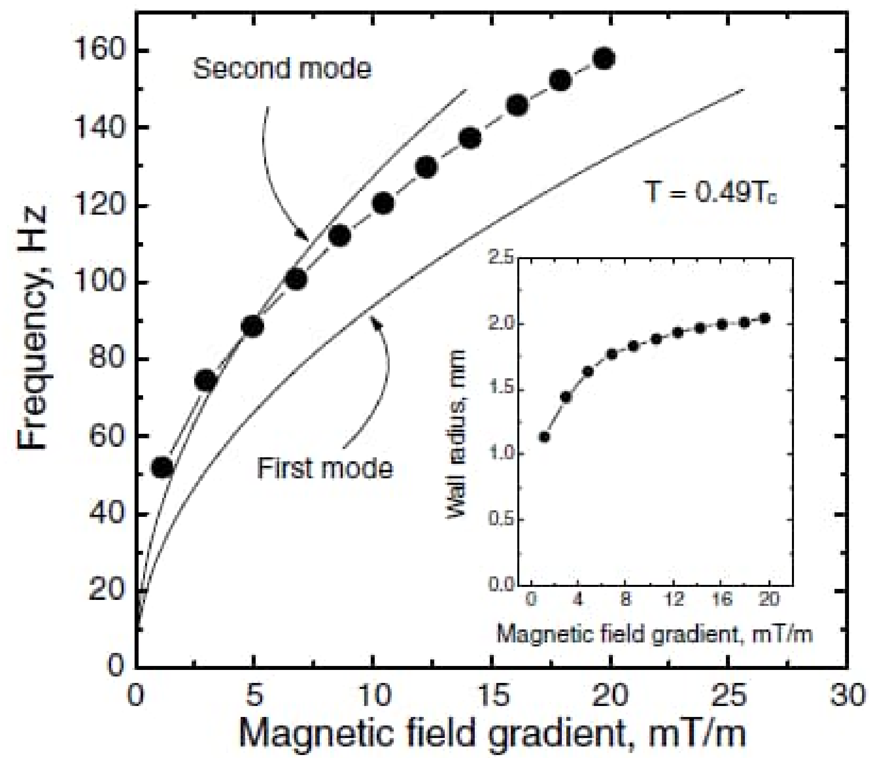




E. Gažo, et al., PRL. 91 55301 (2003)

Goldstone mode of BEC of Magnons in 3He-B





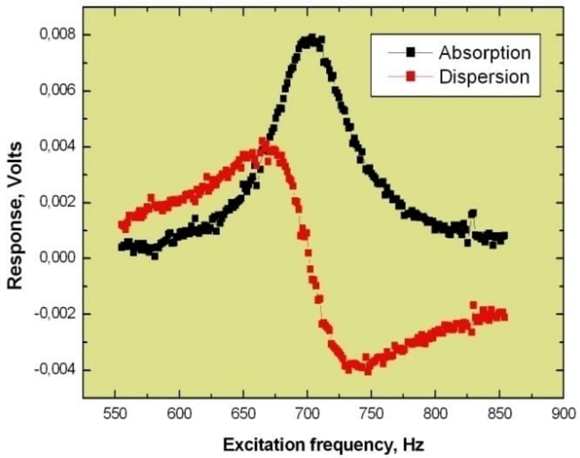
Axial mode:

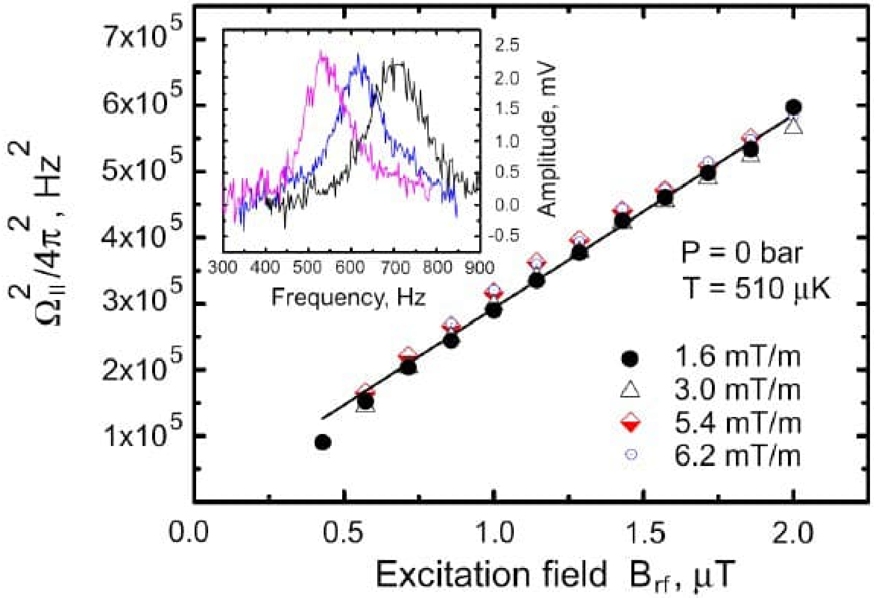
$$\Omega_{Sm}^2 = Q_{im}\frac{c_1 c_2}{RB}\tanh\left(Q_{im}L\frac{c_2}{R2c_1}\right)\nabla B$$

Theory of the Goldstone mode – oscillation of the free decaying HPD

Non-Goldstone collective mode of magnon BEC in superfluid 3He-B

Presence of rf-field B_{RF} violates U(1) symmetry of the precessing state





Influence of B_{RF}, dipole-dipole Interaction, gradient energy

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\xi}}\right) - \frac{\partial L}{\partial \xi} = 0$$

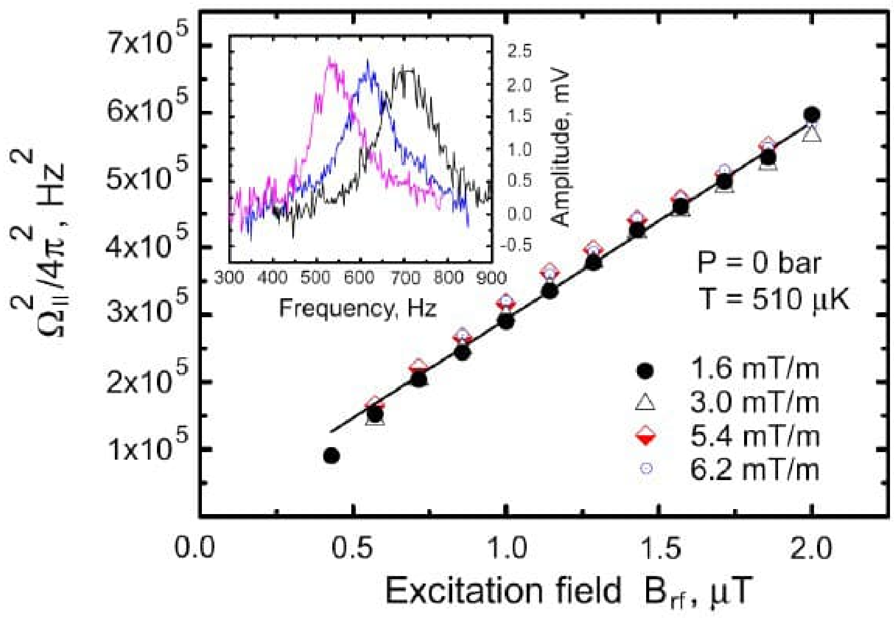
$$\Omega^2 = \frac{\Omega_B^2}{\omega_L^2 + \Omega_B^2}\left[\frac{4}{\sqrt{15}}\gamma B_{rf}\,\omega_L + \frac{c_s^2 \pi^2}{4L^2}\right]$$

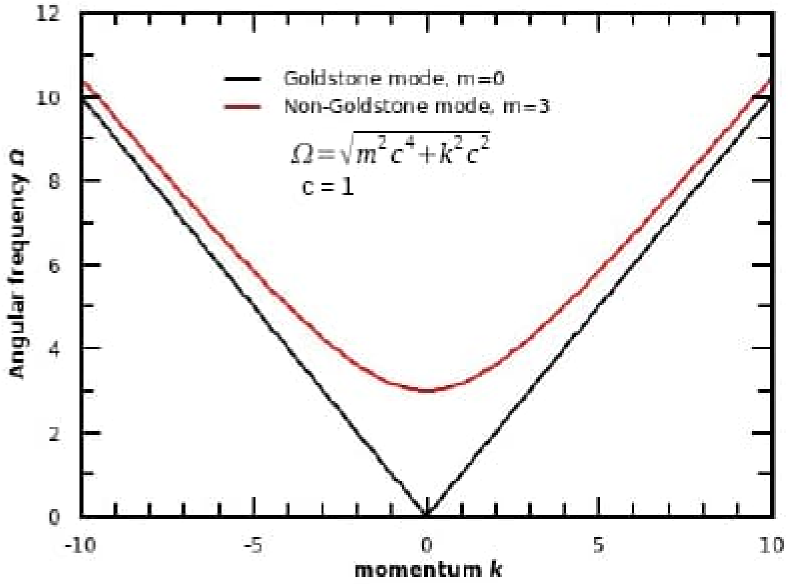
'energy gap' torsional mode

ξ – Euler angles, α, β, γ

Independent on field gradient

Non-Goldstone collective mode of magnon BEC in superfluid 3He-B





$$\Omega^2 = \frac{\Omega_B^2}{\omega_L^2 + \Omega_B^2}\left[\frac{4}{\sqrt{15}}\gamma B_{rf}\,\omega_L + \frac{c_s^2\pi^2}{4L^2}\right]$$

$$E^2 = m^2c^4 + p^2c^2$$

Symmetry breaking rf - field

Non-Goldstone collective mode of BEC of magnons in superfluid 3He-B

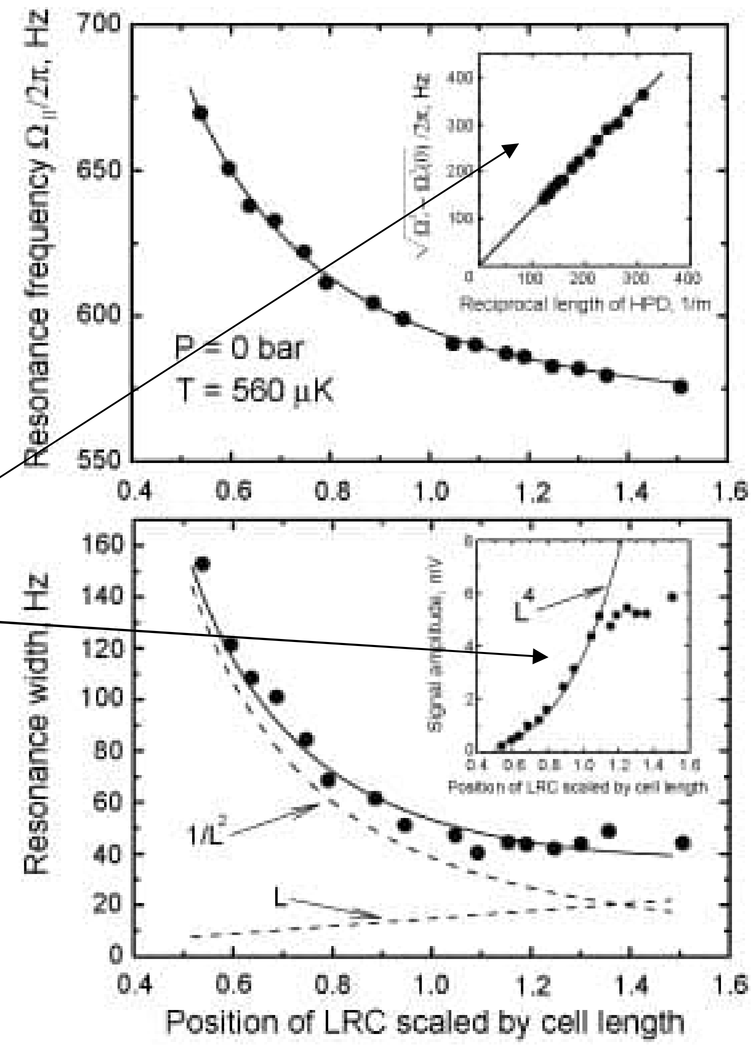
Resonance frequency:

$$\Omega^2 = \frac{\Omega_B^2}{\omega_B^2 + \Omega_B^2}\left[\frac{4}{\sqrt{15}}\gamma B_{rf}\omega_L + \frac{c_s^2\pi^2}{4L^2}\right]$$

Energy gap

Torsional mode

Presence of the torsional oscillations



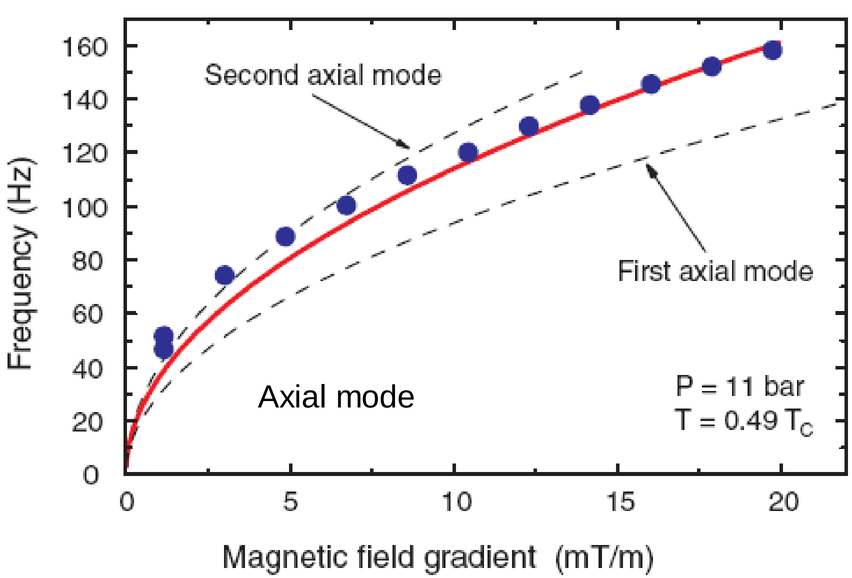
Rate of energy dissipation:

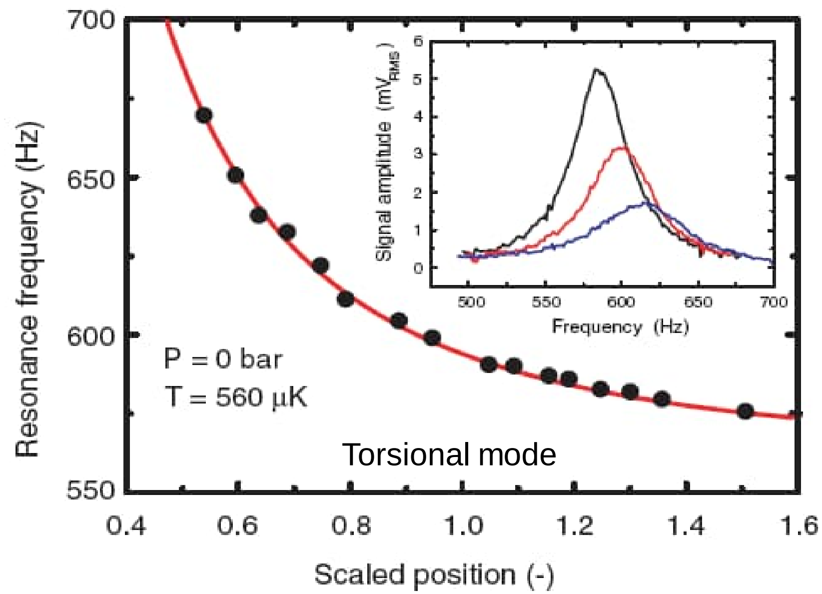
$$\frac{dQ}{dt} = A\frac{D}{L^2} + B\tau_{LT}L$$

M. Clovecko et al., PRL 100, 155301 (2008)

Non Goldstone mode of BEC of Magnons in 3He-B (summary)

Presence of rf-excitation field B_{RF} breaks U(1) symmetry of the precessing states

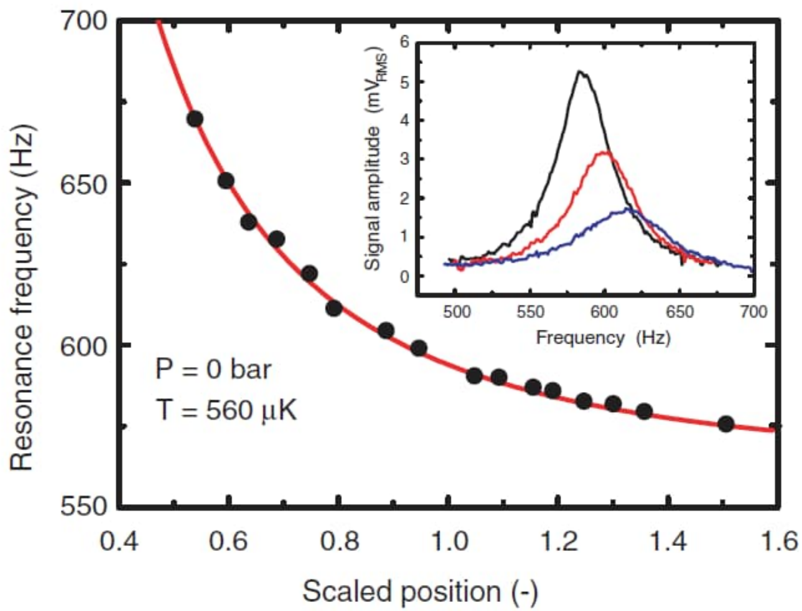


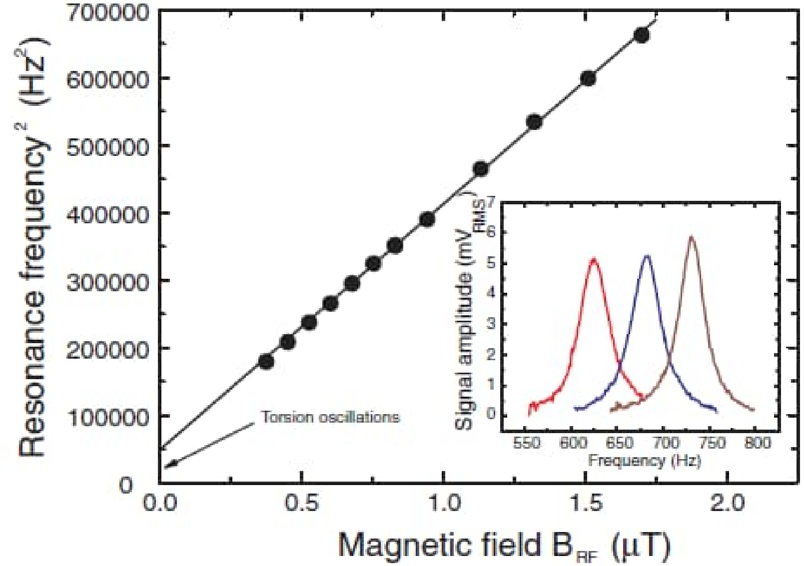


$$\omega^2 = \frac{3\Omega_B^2}{8\Omega_B^2 + 3\omega_{\rm rf}^2}\left[\frac{4}{\sqrt{15}}\,\omega_{\rm rf}\, g\, B_{\rm rf} + \frac{1}{3}(5c_L^2 + 3c_T^2)\left(\frac{\xi_{m,i}}{R}\right)^2 + \frac{2}{3}(5c_T^2 - c_L^2)\left[\frac{(2n+1)\frac{\pi}{2}}{L}\right]^2\right].$$

M. Kupka and P. Skyba, PRB 85 184529 (2012)

Non Goldstone mode of BEC of Magnons in 3He-B as quantum resonant amplifier



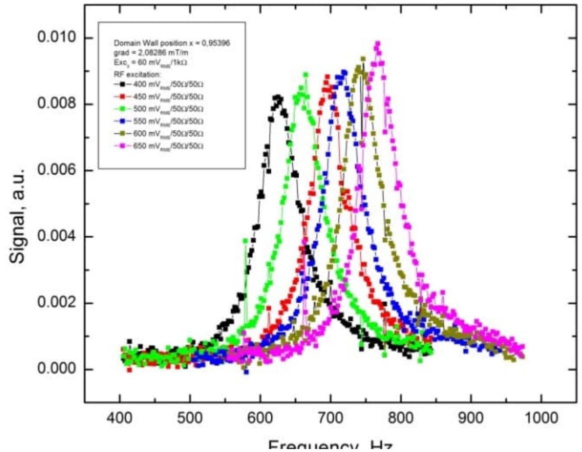


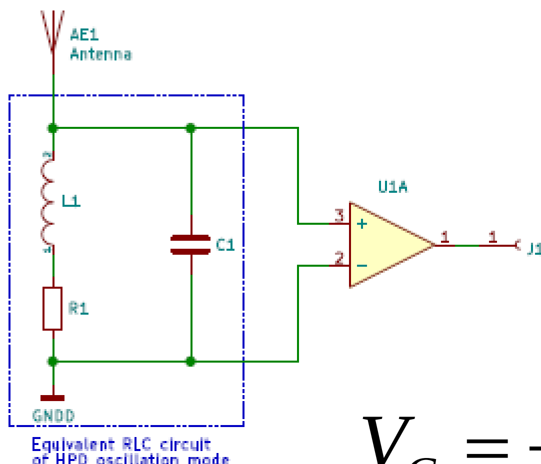
NMR in rotating frame of the reference – HPD is a coherent system

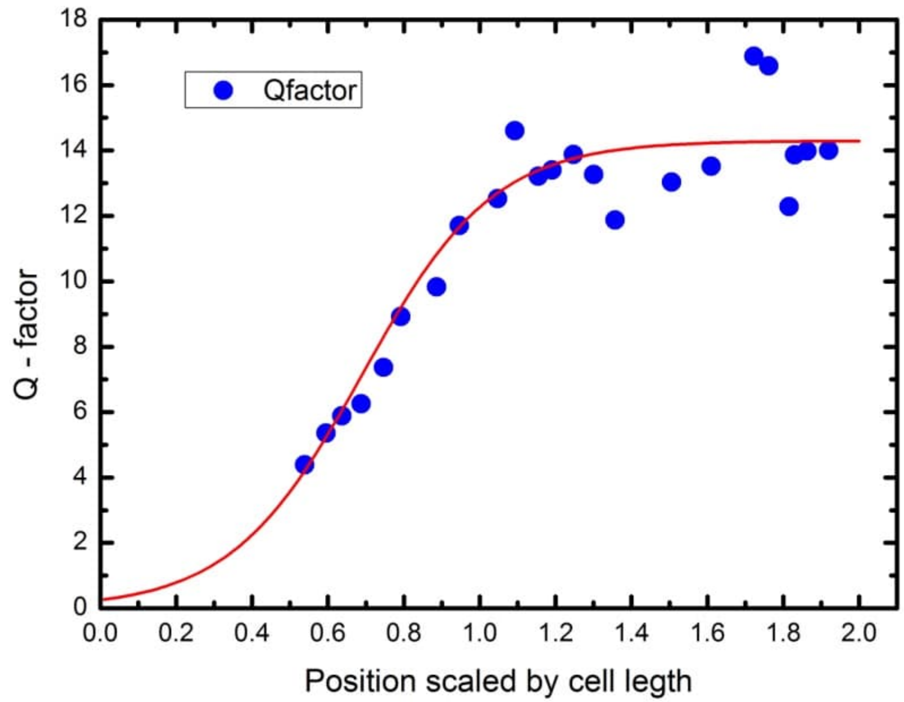
$$\Omega^2 = \frac{\Omega_B^2}{\omega_L^2 + \Omega_B^2}\left[\frac{4}{\sqrt{15}}\gamma B_{rf}\,\omega_L\right]$$

M. Kupka and P. Skyba, PRB 85 184529 (2012)

Non Goldstone mode of BEC of Magnons in 3He-B as quantum resonant amplifier





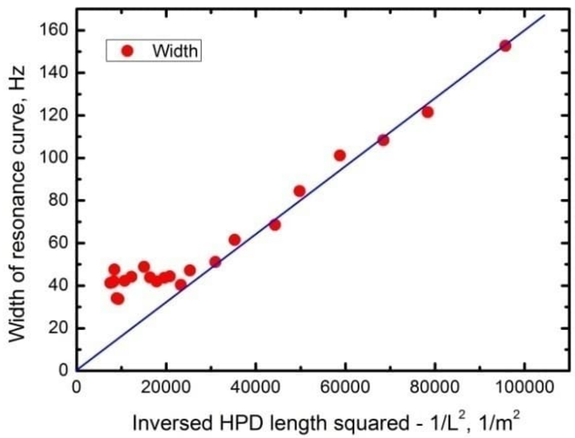


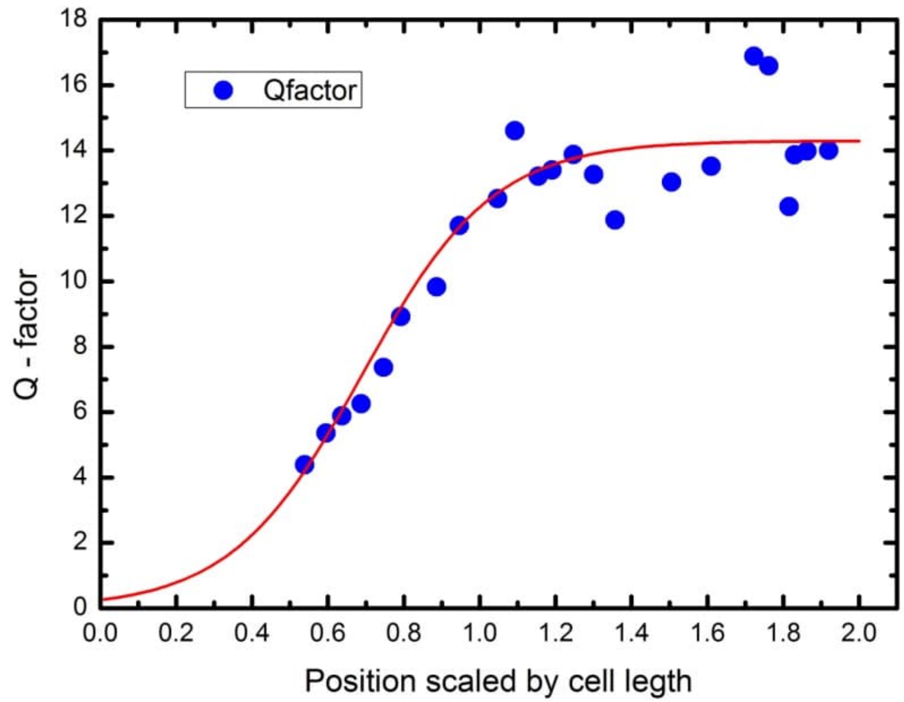
$$V_C = -jQV_i$$

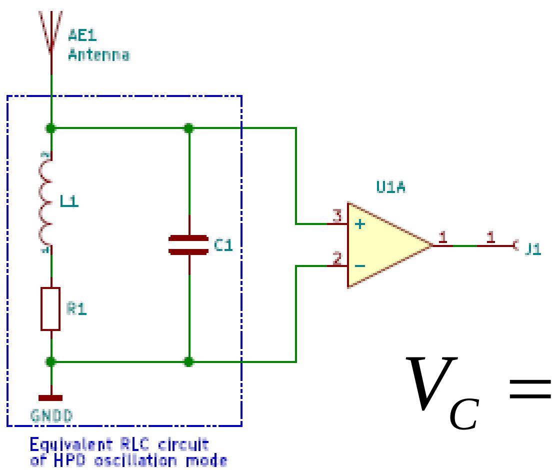
$$\Omega^2 = \frac{\Omega_B^2}{\omega_L^2 + \Omega_B^2}\left[\frac{4}{\sqrt{15}}\gamma B_{rf}\,\omega_L\right]$$

Frequency tuning

Non Goldstone mode of BEC of Magnons in 3He-B as quantum resonant amplifier







$$V_C = -jQV_i$$

$$\Omega^2 = \frac{\Omega_B^2}{\omega_L^2 + \Omega_B^2}\left[\frac{4}{\sqrt{15}}\gamma B_{rf}\omega_L\right]$$

Frequency tuning

Conclusion

Demonstration of the collective mode of BEC of magnons in 3He-B as a new type of quantum resonant amplifier:

- in principle it the NMR in rotating frame of reference
- tunanble by two parameters
- should be universal feature for any type of NMR

Thank you for your attention