Superfluid 3He-B as a model system for Q-bit

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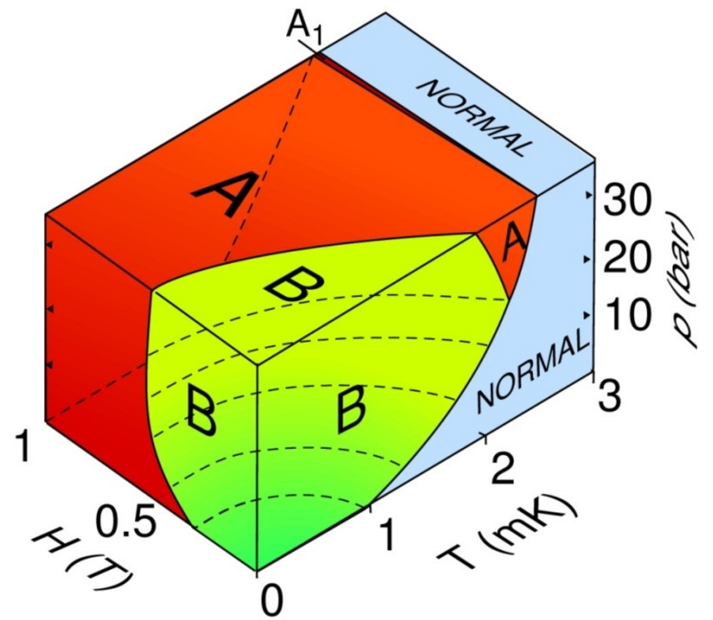
CENTRE · LOW TEMPERATURE PHYSICS · KOŠICE SLOVAKIA

Superfluid 3He - as a model system

Helium-3 phase diagram

Normal 3He - Fermi liquid



Phase transition into superfluid state (N phase → A phase or N phase → B phase) is of second order phase transition associated with:
- spontaneously broken symmetry,
- appearance of the energy gap in spectrum of excitations.

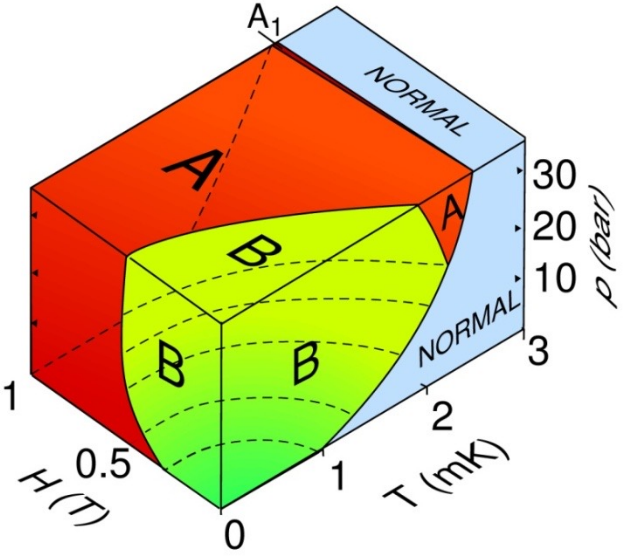
First order phase transition:
A phase → B phase.

$SO^L(3) \times SO^S(3) \times U(1) \rightarrow$ Superfluid 3He

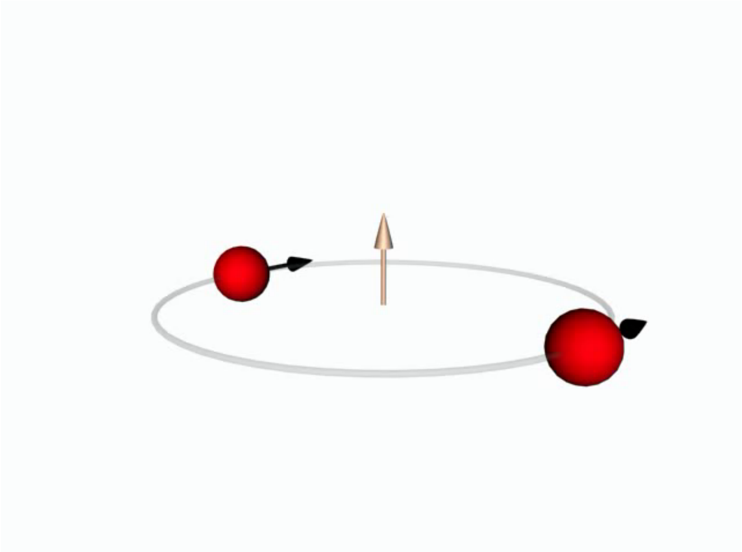
$SU(3) \times SU(2) \times U(1) \rightarrow$ Universe (GUT)

Superfluid 3He

Phase diagram



Cooper pairs creation



Spin triplet state S = 1
Orbital p-wave L = 1

General wave function (or order parameter):

$$\Psi(\vec{k}) = \Psi_{\uparrow\uparrow}(\hat{k})\left|\uparrow\uparrow\right\rangle + \Psi_{\downarrow\downarrow}(\hat{k})\left|\downarrow\downarrow\right\rangle + \sqrt{2}\Psi_{\uparrow\downarrow}(\hat{k})\left(\left|\uparrow\downarrow\right\rangle + \left|\downarrow\uparrow\right\rangle\right)$$

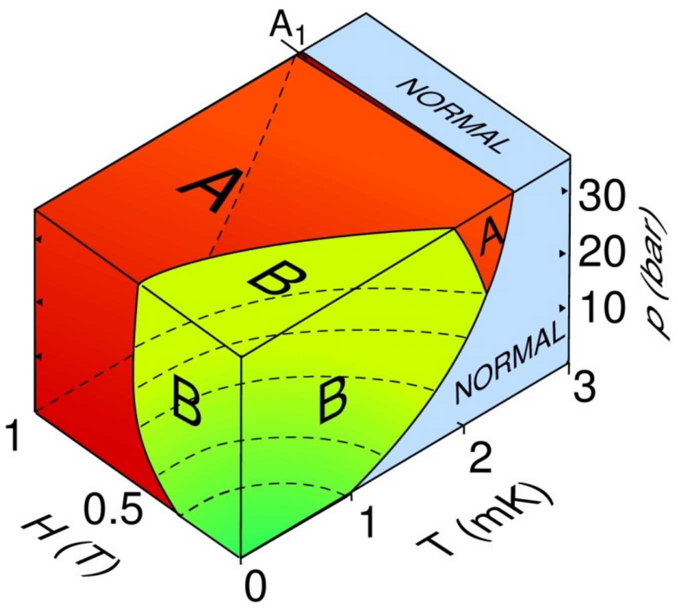
Vector representation:

$$\boxed{d_\nu(\vec{k}) = \sum_\mu A_{\nu\mu} k_\mu}$$

Dipole –dipole interaction

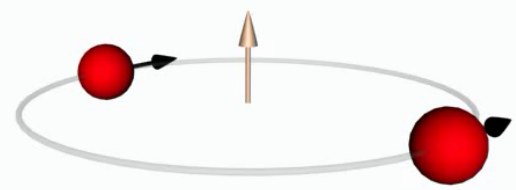
Superfluid 3He

Phase diagram



Cooper pairs creation

Spin ^{3}He quasiparticle = 1/2



Spin triplet state S = 1
Orbital p-wave L = 1

Wave function (or order parameter):

$$\Psi = \Psi_L(\vec{k})\Psi_S(\vec{k})$$

orbital part **spin part**

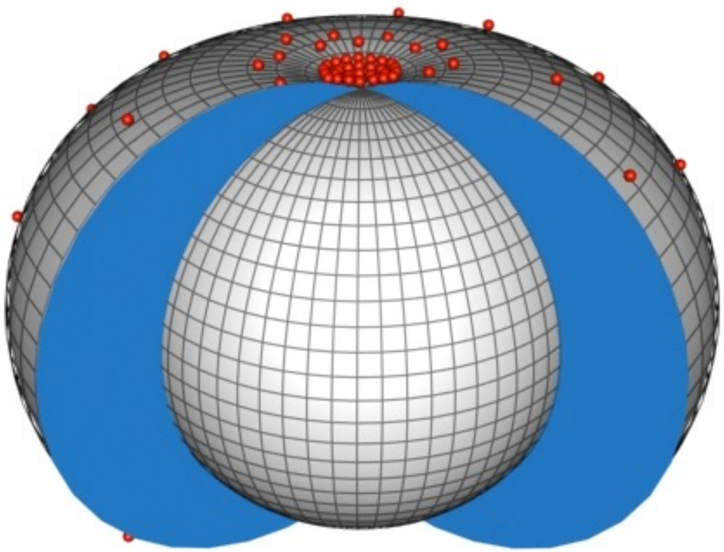
$$g_D(T) \approx \frac{\mu_0^2}{a^3}\left[\frac{\Delta(T)}{E_F}\right]^2 n$$

Dipole –dipole interaction

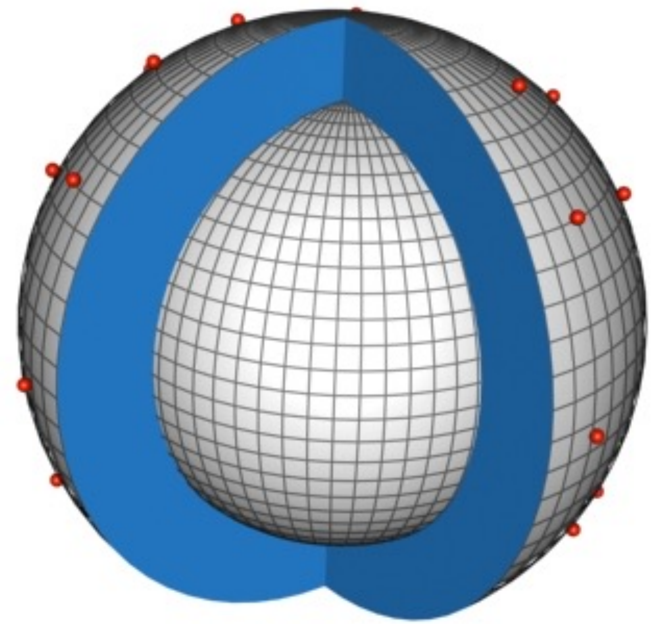
Spectrum of quasiparticle excitations

A-B boundary – connecting two different physical vacuum

^{3}He-A phase



^{3}He-B phase

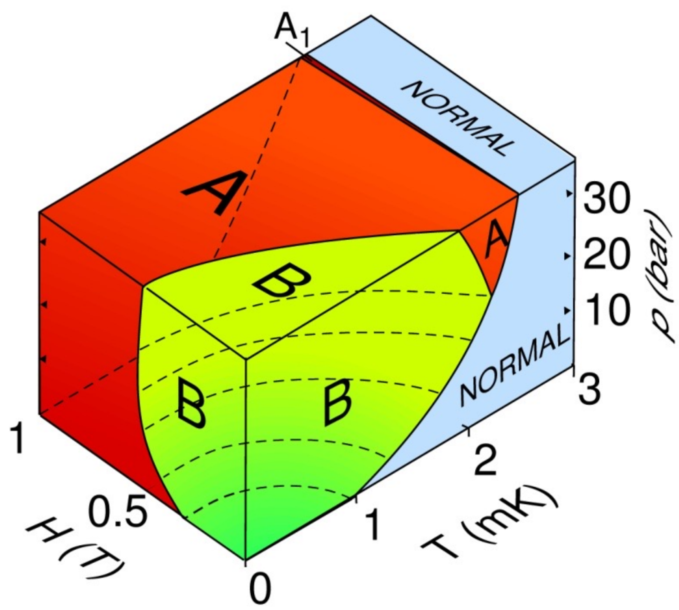


^{3}He-A – many excitations at Fermi points. Excitation density varies as T^3 at very low temperatures.

^{3}He-B – low excitation density at very low temperatures. Symmetric energy gap.

Superfluid 3He as model system

Phase diagram



Wave function (or order parameter):

$$\Psi = \Psi_L(\vec{k})\Psi_S(\vec{k})$$

orbital part

spin part

NMR in Superfluid 3He

$$\dot{\vec{S}} = \gamma\vec{S} \times \vec{B}(t) + \vec{R}_D$$

$$\dot{\vec{d}} = \vec{d} \times \gamma\vec{B}_{eff}$$

$$\vec{B}(t) = \vec{B}_0 + \vec{B}_{rf}(t) \qquad \vec{B}_{eff} = \vec{B}(t) - \frac{\gamma\vec{S}}{\chi_0}$$

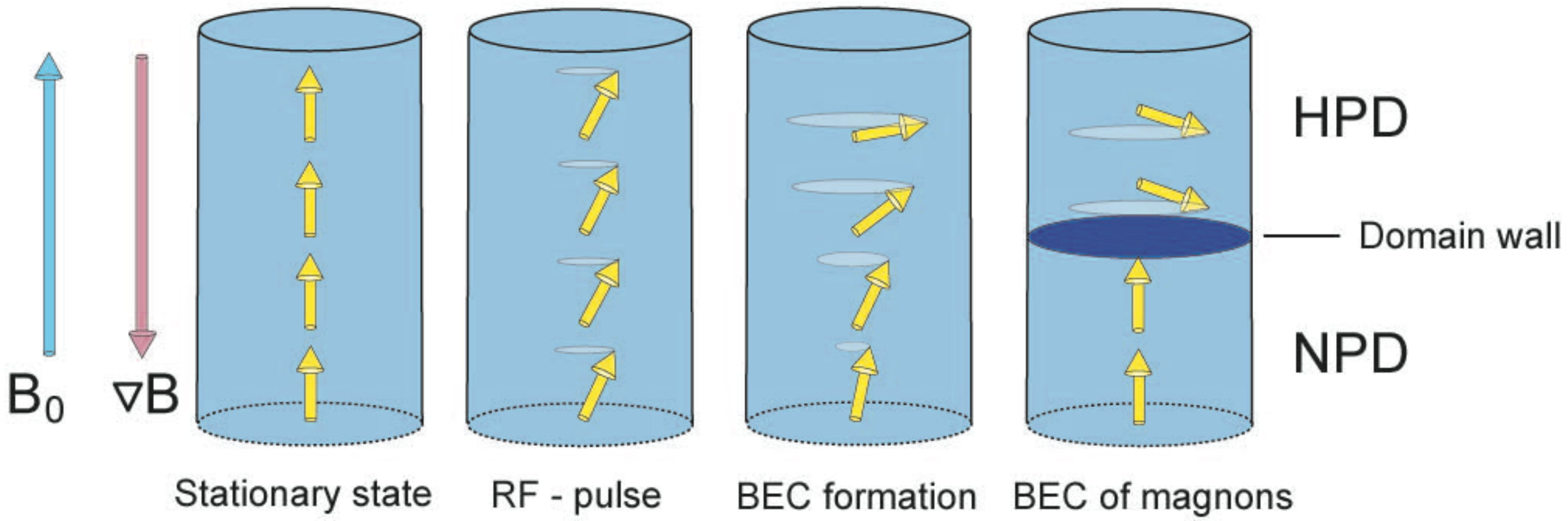
Dipole –dipole interaction

$$E_{dip} \approx g_D(T)\left[(1+\cos\beta).(1+\cos\Phi) - \frac{3}{2}\right]^2$$

Spin super-currents

$$J_{i\alpha} = \frac{\hbar}{2m_{3He}}\rho_{ij\alpha\beta}\Omega_{j\beta}$$

Formation of BEC of magnons



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

Wave function:

$$\Psi = \Psi_L(\vec{k})\Psi_S(\vec{k})$$

spin part →

$$\Psi_S = |\Psi_{S0}|.e^{i\alpha}$$

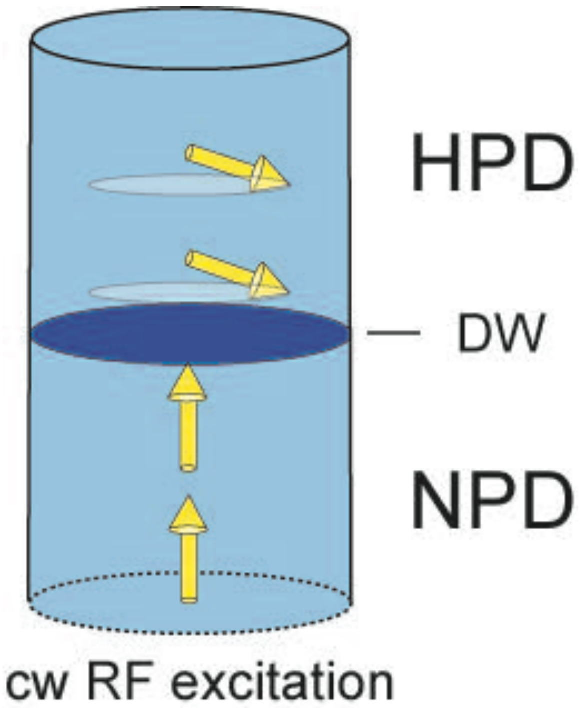
α – is the phase of spin precession

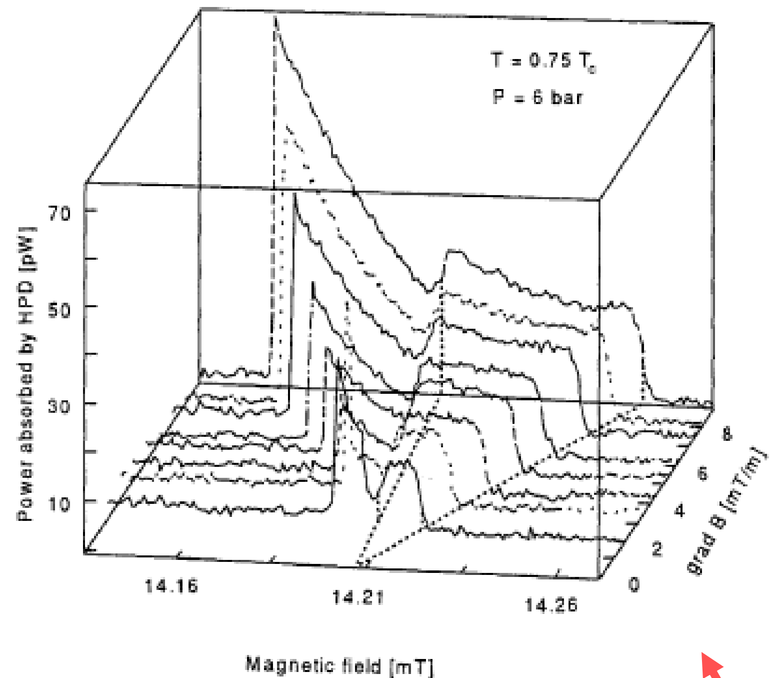
$$\nabla\alpha \neq 0 \rightarrow currents$$

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

Coherently spin precessing states – evidence of BEC of magnons

cw – NMR method





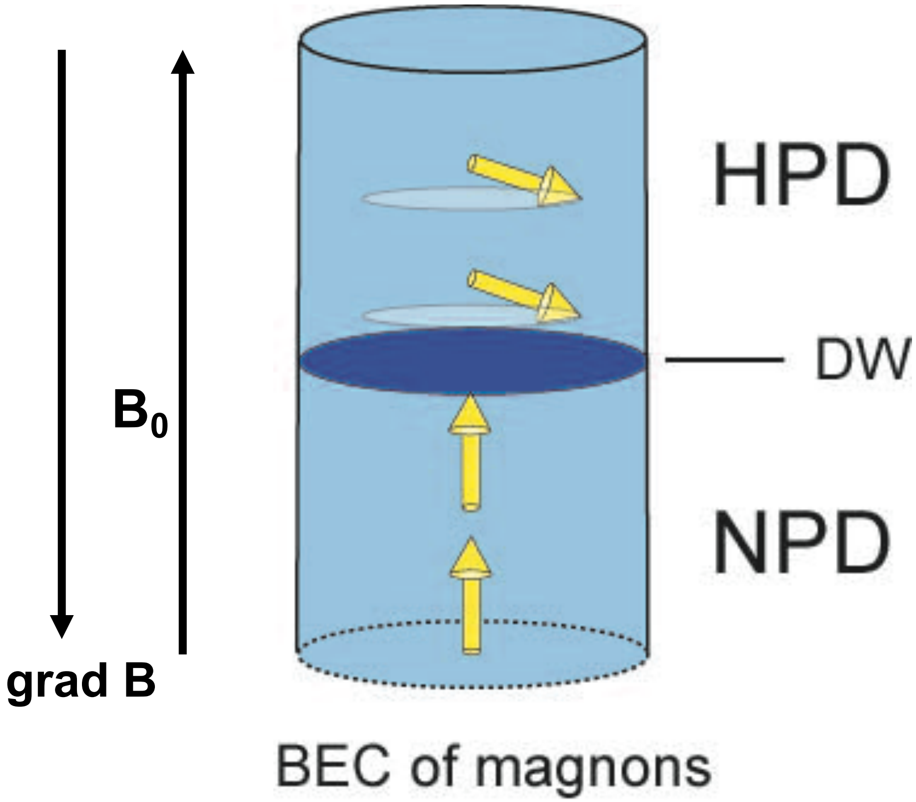
Energy dissipation due to presence of quasiparticle excitations.

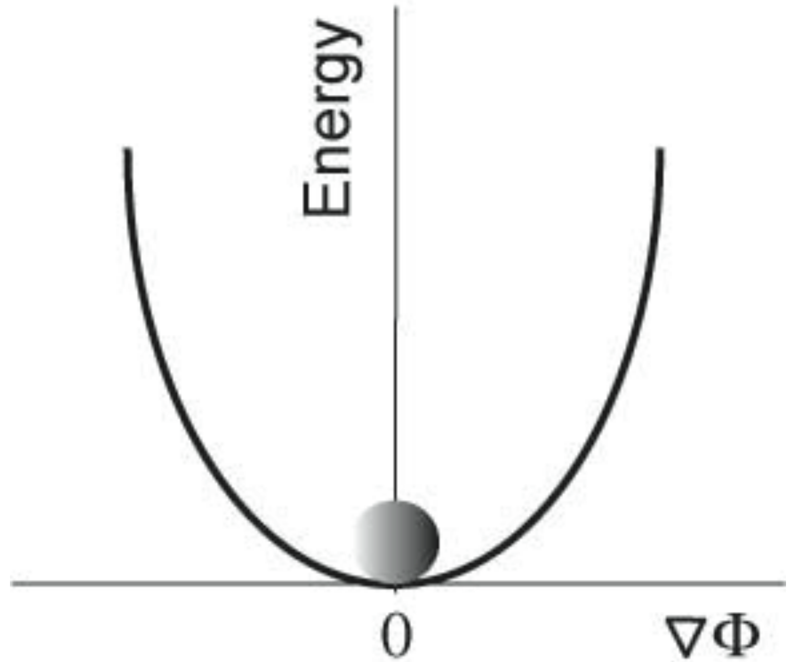
cw – NMR method compensates energy losses due to dissipation, the HPD can be continuously maintained.

Larmor resonance condition →

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

Coherently spin precessing states – evidence of BEC of magnons





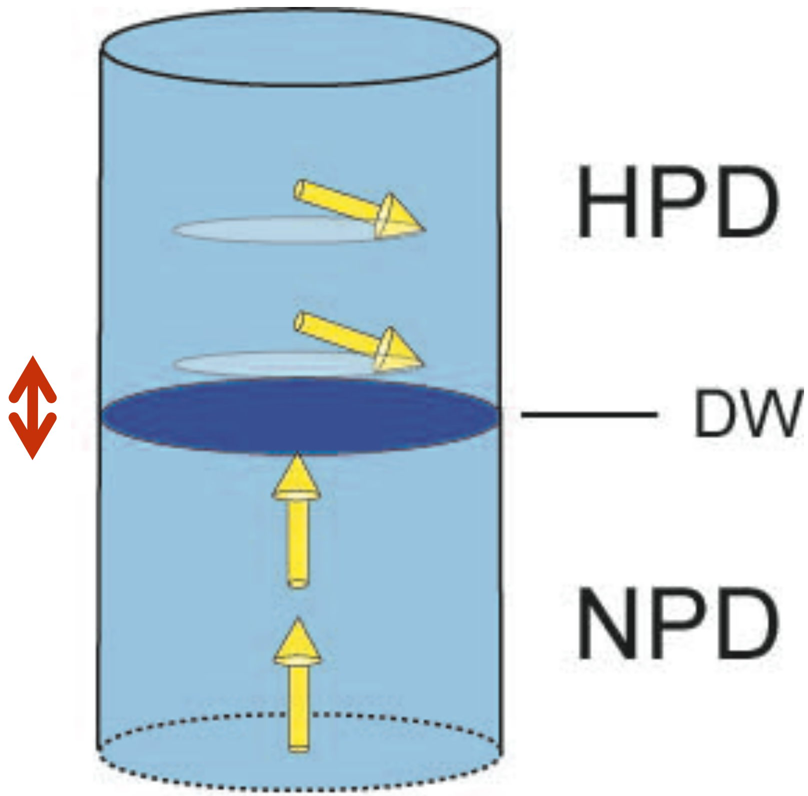
$$\Psi_S = \left|\Psi_{S0}\right| . e^{i\Phi}$$

Dynamical equilibrium state state, state of minimum energy.

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

Simplified expression.

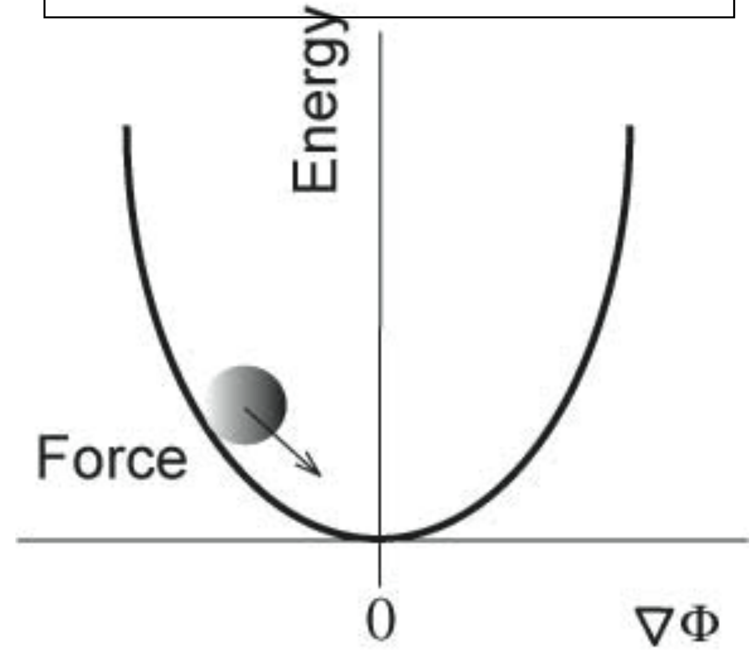
Coherently spin precessing states – evidence of BEC of magnons



BEC of magnons

Perturbation – additional field

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

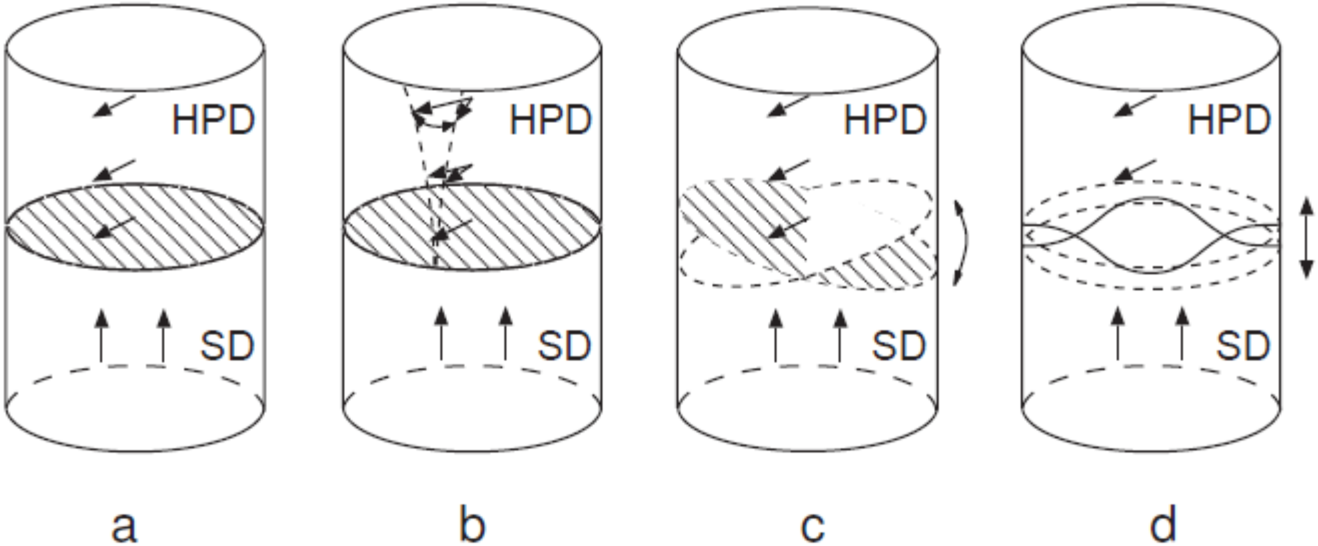


Deflection from energy minimum

Oscillations around minimum
Goldstone (phonon) mode

(Non) Goldstone oscillation modes of HPD
(spin precession waves)

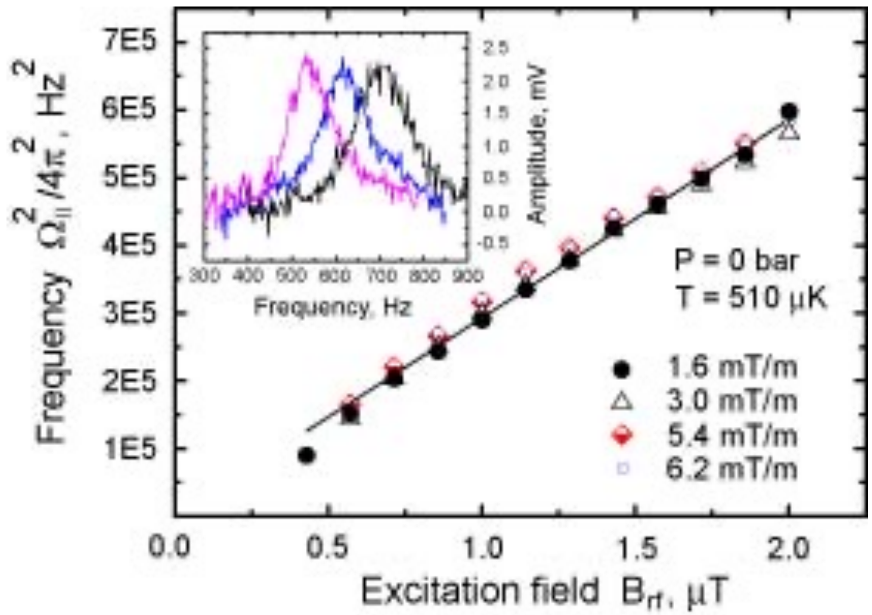
Deflection of the HPD from ground state may lead to generation of the Goldstone collective oscillation modes:

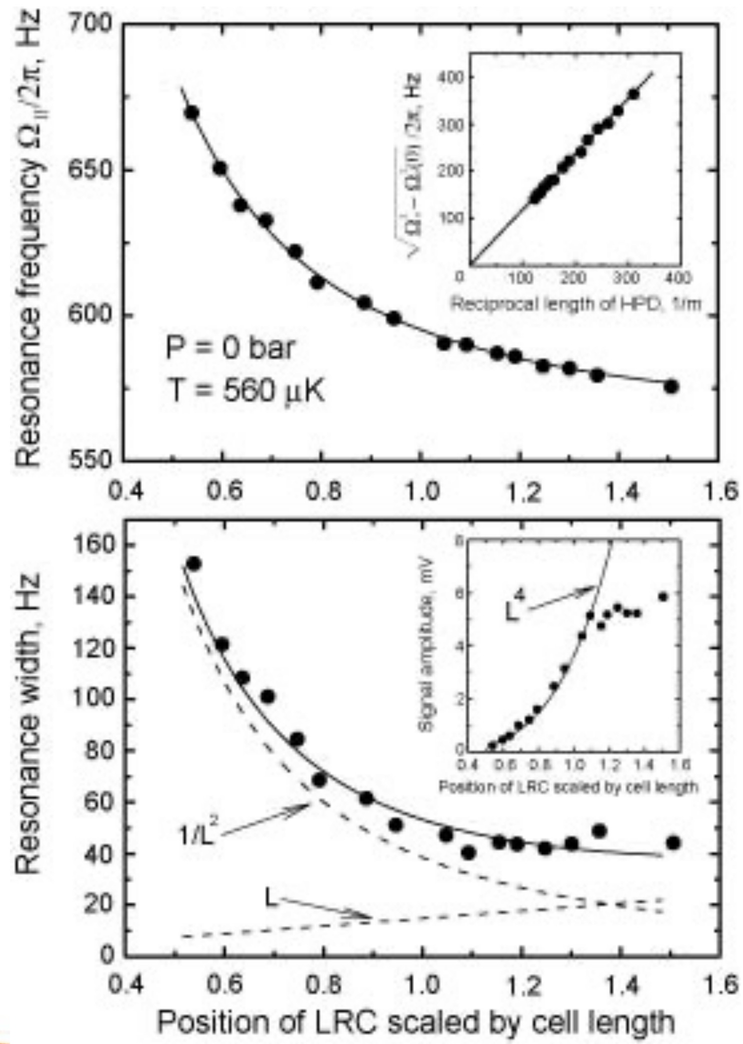


Schematic visual representation of the HPD–SD oscillation modes:
HPD stationary state (a),
torsion mode (b), planar mode (c) and first axial mode (d)

Yu.M. Bunkov et al., JETP Lett. 43, 168 (1986)
Yu.M. Bunkov et al., Physica 178B 196 (1992)
E. Gažo, et al., Phys.Rev. Lett. 91 55301 (2003)
I.A. Fomin, JETP Lett. 43 171 (1986)

Non Goldstone mode of BEC of Magnons in 3He-B



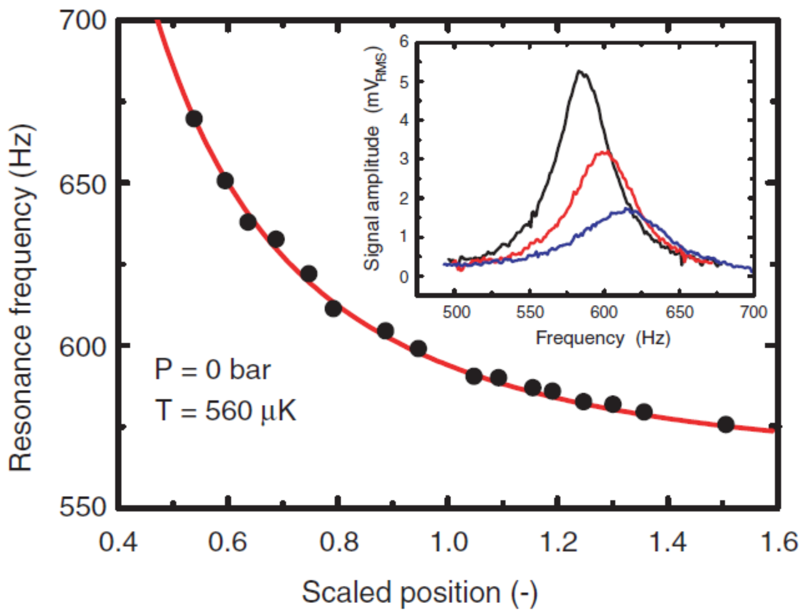


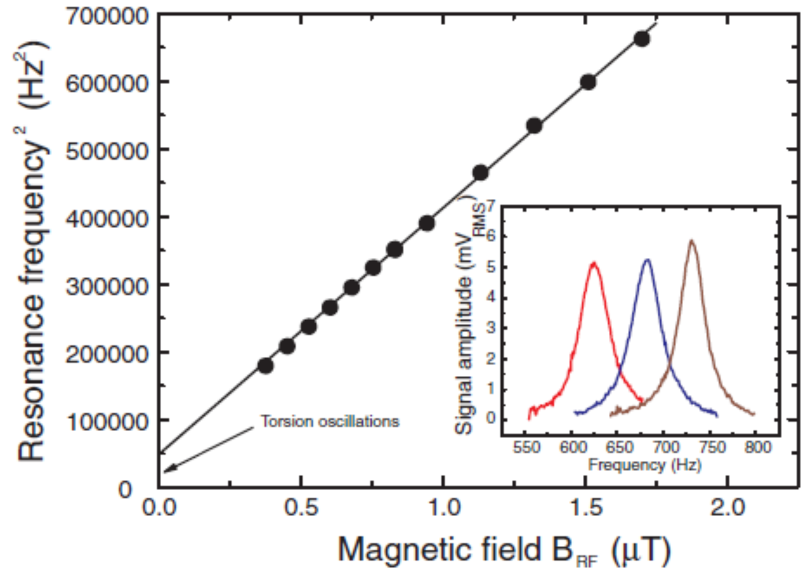
$$\Omega^2 = \frac{\Omega_B^2}{\omega_L^2 + \Omega_B^2}\left[\frac{4}{\sqrt{15}}\gamma B_{rf}\omega_L + \frac{c_s^2\pi^2}{4L^2}\right]$$

$$E^2 = \left(m_0c^2\right)^2 + \left(c.p\right)^2$$

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

Non Goldstone mode of BEC of Magnons in 3He-B as model system for Q-bit





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

Kupka and Skyba PRB 85 184529 (2012)

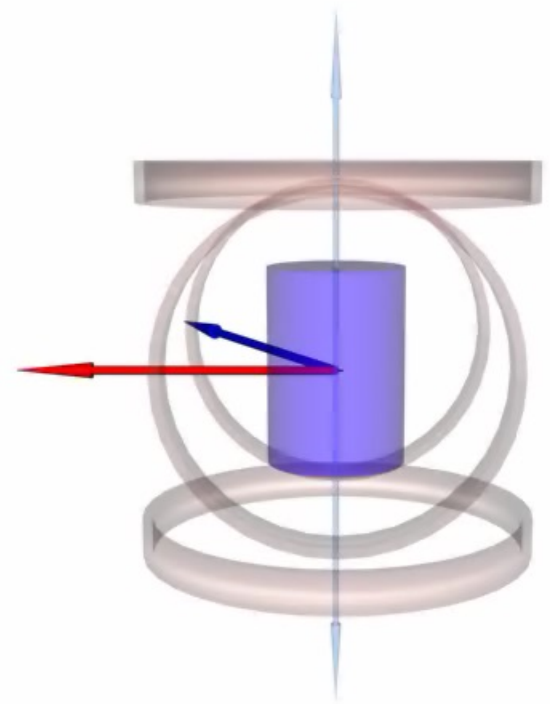
HPD as a model system for Q-bit

Simplified equation for Q-bit

$$\Psi = a|0\rangle + b|1\rangle$$

Pulsed NMR in rotating frame
of the reference

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



Kupka and Skyba PRB 85 184529 (2012)

Volume for HPD

3 pairs of coils on axles
(X, Y, Z) for NMR

Vibrating wire and tuning fork

Array of 5 tuning forks,
vibrating wire and tuning fork

Silver heat exchanger

Conclusion

Experiment is in progress and I shall inform you on results. I hope soon.