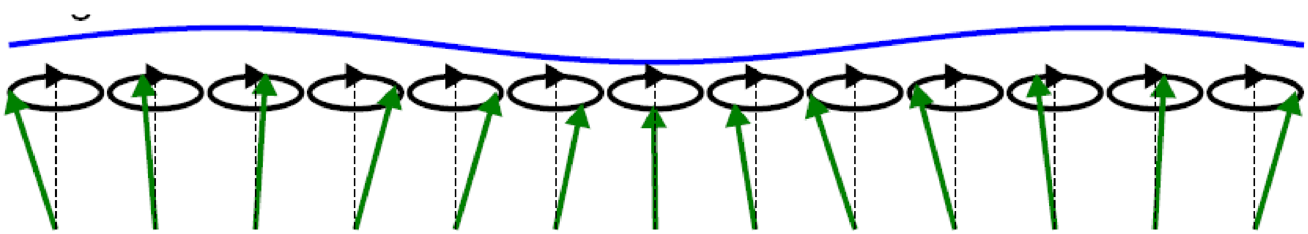
Spin superfluidity in antiferromagnets

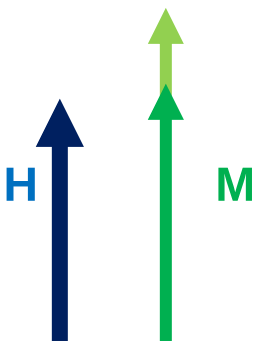
Yu. M. Bunkov

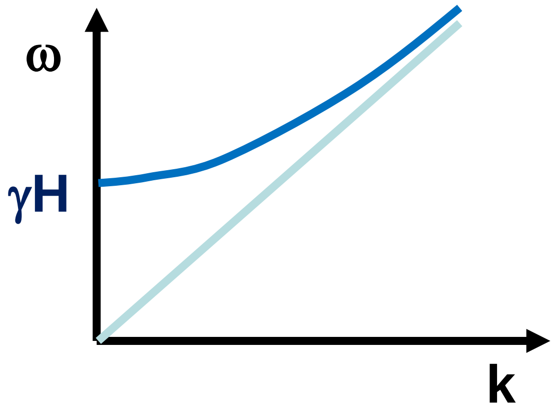
Institute Neel, CNRS, Grenoble, France

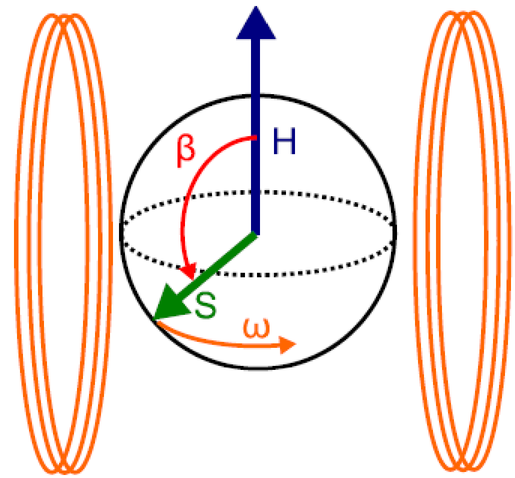
OIST, 2012

Spin waves



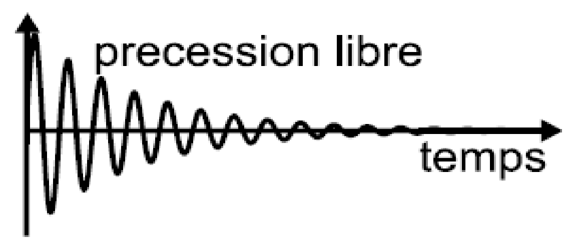


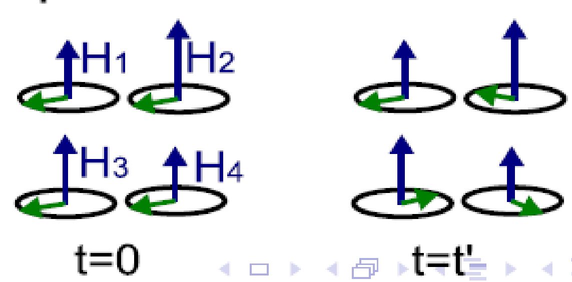




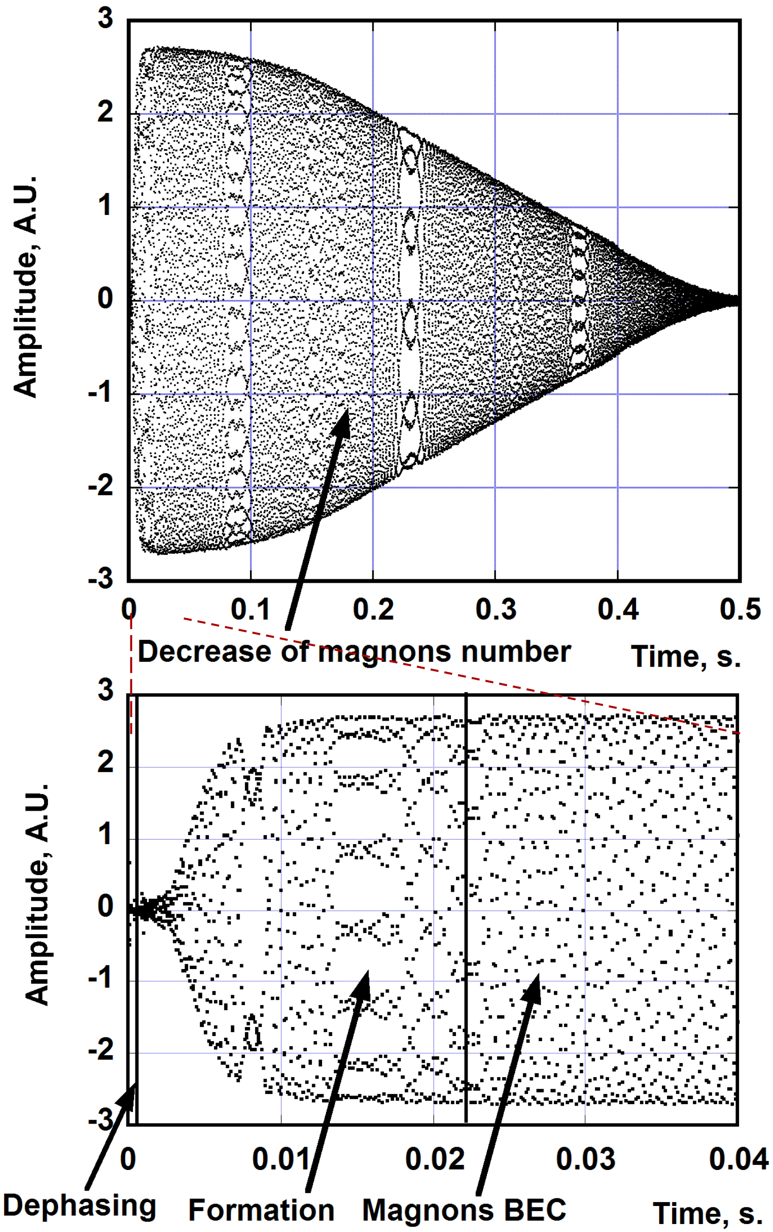
Holstain-Primakoff transformation

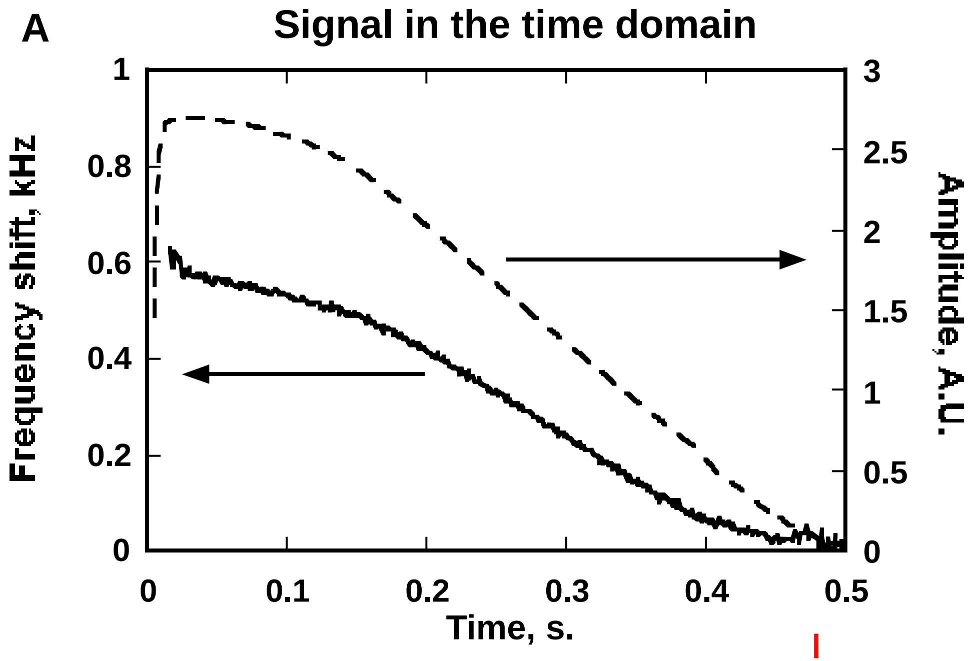
$$\begin{cases} \widehat{S}_+ = \sqrt{2S\hbar}\,\widehat{a_0}\sqrt{1-\dfrac{\hbar\widehat{a_0}^{\dagger}\widehat{a_0}}{2S}} \\ \widehat{S}_- = \sqrt{2S\hbar}\sqrt{1-\dfrac{\hbar\widehat{a_0}^{\dagger}\widehat{a_0}}{2S}}\,\widehat{a_0}^{\dagger} \\ \widehat{S}_z = S-\hbar\widehat{a_0}^{\dagger}\widehat{a_0} = S-\hbar\widehat{N_0} \end{cases}$$





Grenoble, 2003

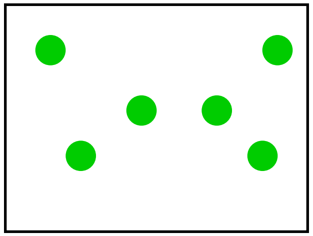




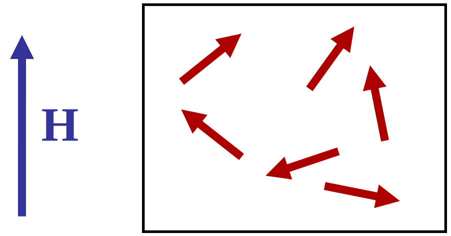
The main landmark of BEC is the changing of frequency at relaxation. The magnon dencity decay changes the chemical potencial!

The first observation:

A.S.Borovik-Romanov, Yu.M.Bunkov, V.V.Dmitriev, Yu.M.Mukharskiy, JETP Letters v.40, p.1033, (1984).
I.A.Fomin, JETP Letters v.40, p.1036, (1984).

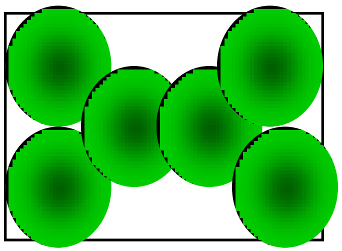


Ideal gas

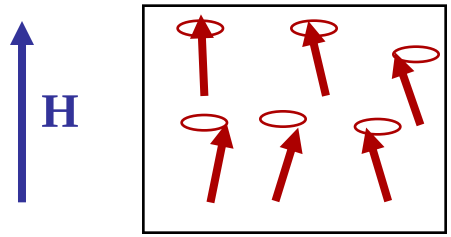


$$\omega=\gamma H_{loc}$$

Paramagnetic, Fermi liquid

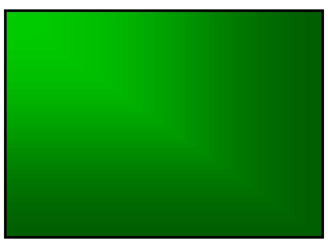


Quantum gas

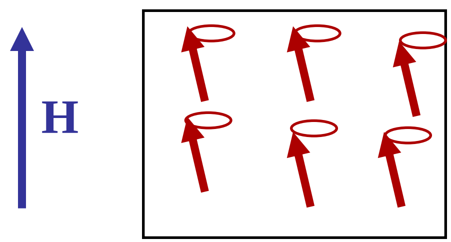


$$i\hbar\frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m}\nabla^2\psi + V\psi$$

Magnetically ordered



BEC, superfluidity



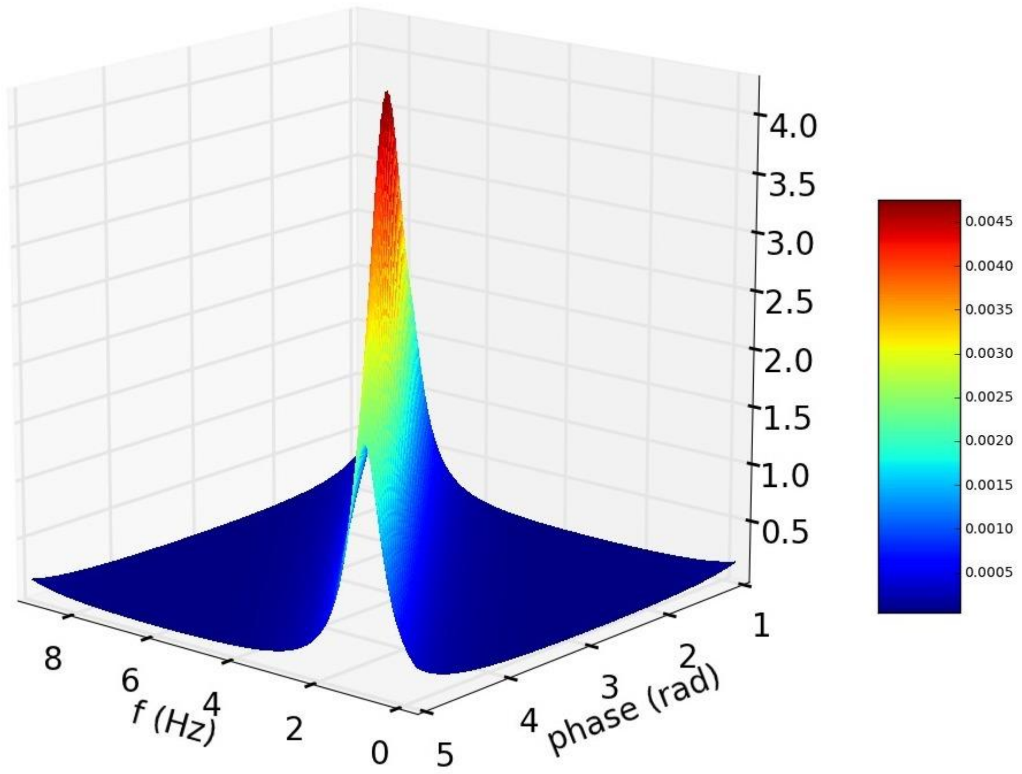
$$\omega=\omega_0$$

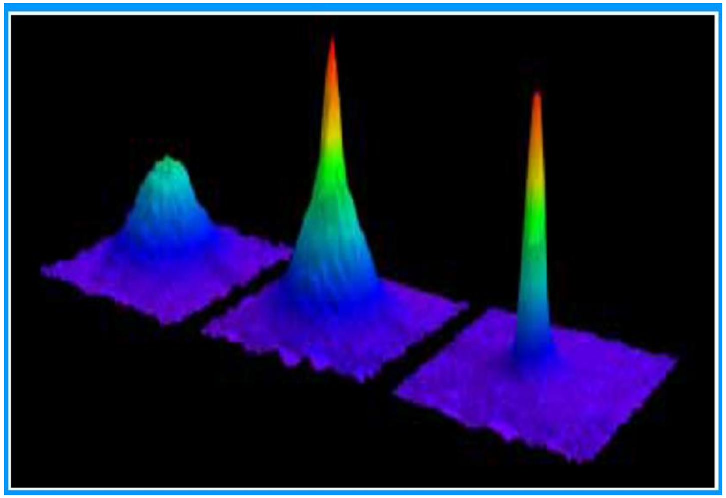
$$S_x + iS_y = S\,\sin\beta\, e^{\,i\omega t\,+i\alpha}$$

Coherent precession

Spin superfluidity and BEC of magnons was found in a 5 different states of superfluid 3He. In one of this states the induction signal can live more then one hours. Its corresponds to a 99.999% of magnons to be condenced! For an atomic BEC the 30% condensation was only achieved!

$$S_x + iS_y = S \, sin \, \beta \, e^{\, i\omega t \, + i\alpha}$$

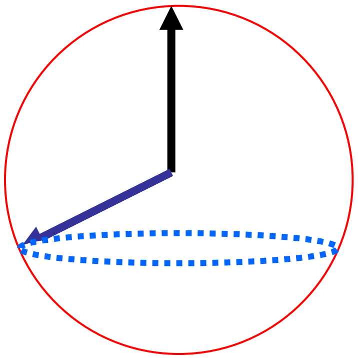




Magnon BEC

Atomic BEC

Spin waves in superfluid ^{3}He are ready to be condensed!



$$N_M = \int d^3r |\Psi|^2 = \int d^3r \frac{S - S_z}{\hbar}$$

$$\Psi = \sqrt{2S/\hbar}\ \sin\frac{\beta}{2}\ e^{i\omega t + i\alpha}\ ,$$

Magnon spectrum

$$\omega(k) = \omega_L - \omega + \frac{c^2k^2}{\omega_L} \equiv \omega_L - \omega + \frac{k^2}{2m_M}$$

Magnon mass

$$m_M \sim \frac{\omega_L}{v_F^2} \sim m_3 \frac{\omega_L}{E_F}$$

($\hbar$ = 1; $c \sim v_F$)

Magnon density

$$n_M \sim S \sim \chi H/\gamma \sim \omega_L N_F \sim n_3 \omega_L / E_F$$

where $N_F \sim m_3 p_F$ is the density of states and $n_3 \sim p_F^3$ is the density of atoms.

Temperature of BEC

$$T_{\rm BEC} \sim \left(\frac{nc^3}{\omega_L}\right)^{1/2} \sim E_F$$

$T_F = 0.1K,\ T_{exp} = 0.0003K$

G.Volovik

Gross-Pitaevskii equation

$$\frac{\delta F}{\delta \Psi^*} = 0$$

Dipole-dipole spin-orbit energy

$$F = \int d^3r \left(\frac{|\nabla \Psi|^2}{2m_M} + (\omega_L(z) - \omega)|\Psi|^2 + F_D \right)$$

I.A. Fomin, Physica **B 169**, 153 (1991).

Gradient energy

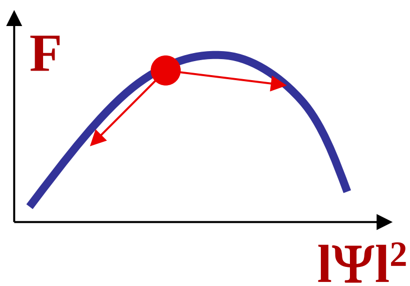
Spectroscopic energy

Spin Supercurrent

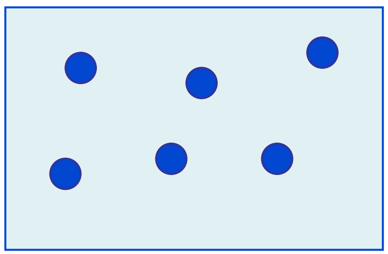
True energy at the rotating frame

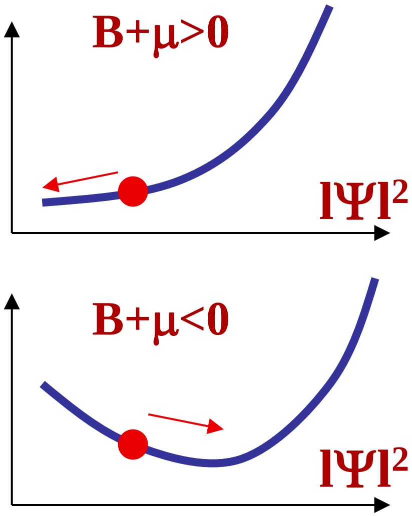
Chemical potential $\mu = \omega_L(z) - \omega$

$$F = A + (B+\mu)\, |\Psi|^2 + C|\Psi|^4$$

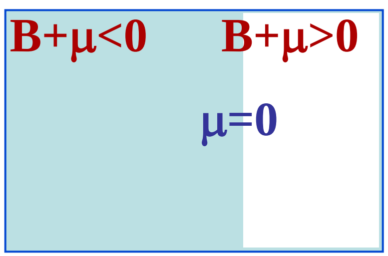


C < 0

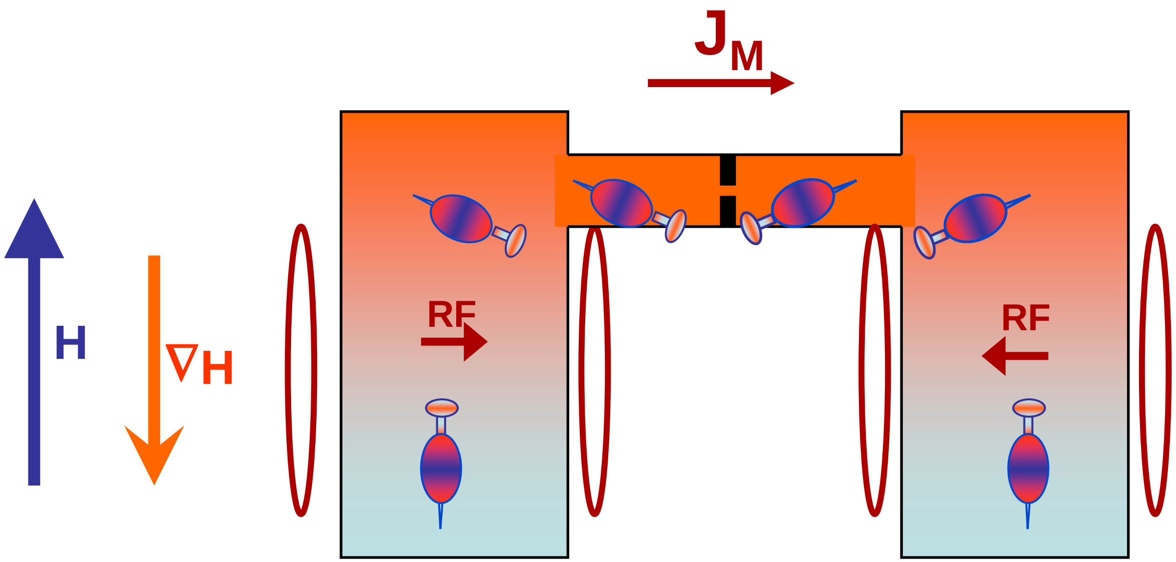




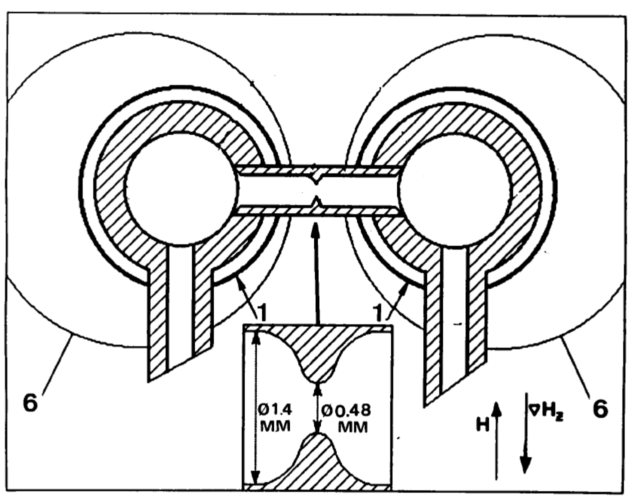
C > 0



Josephson effect

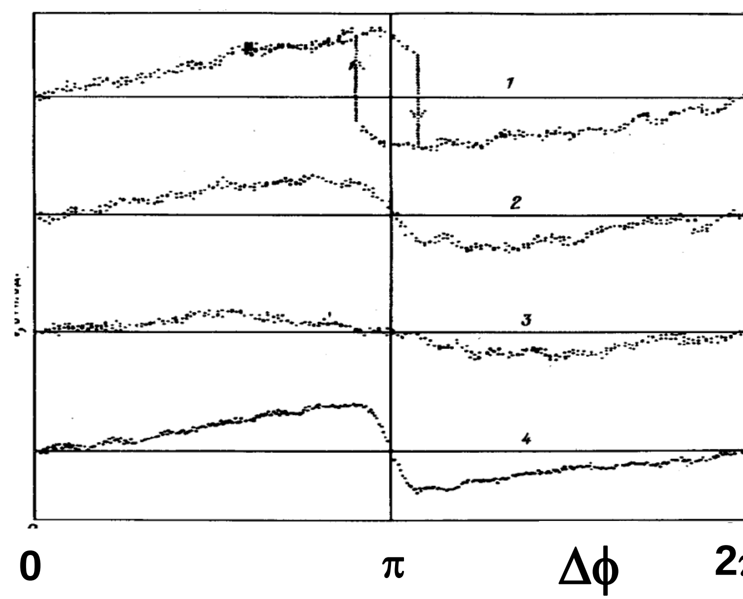


$$\xi = 1.088 c_{\parallel}/\sqrt{\omega(\omega - \gamma H)}$$



JETPh Letters, v.47, p.478, (1988).

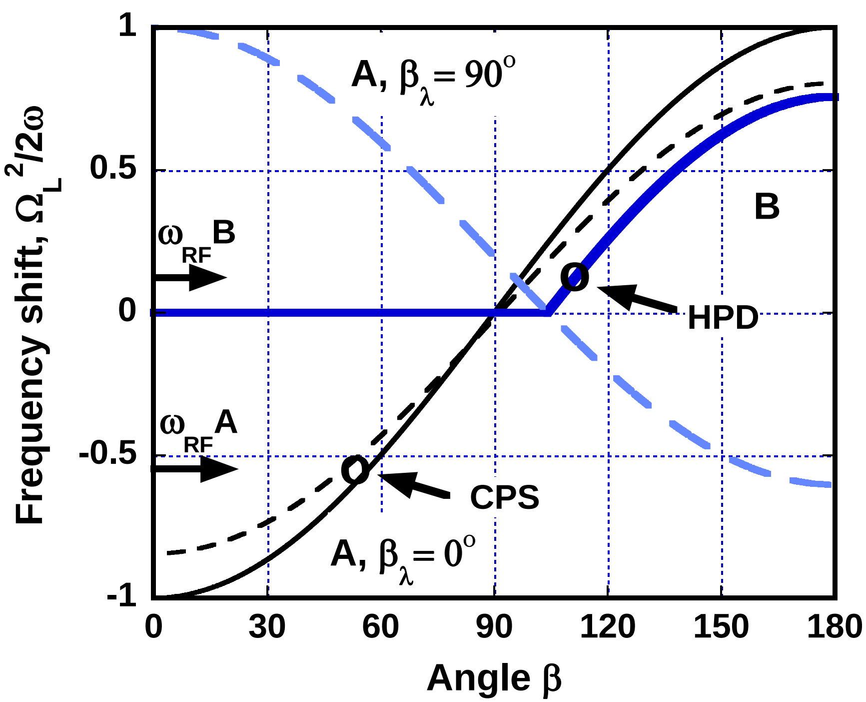
QFS Florida 1989, AIP Conf. Proc., v.194, p.27.

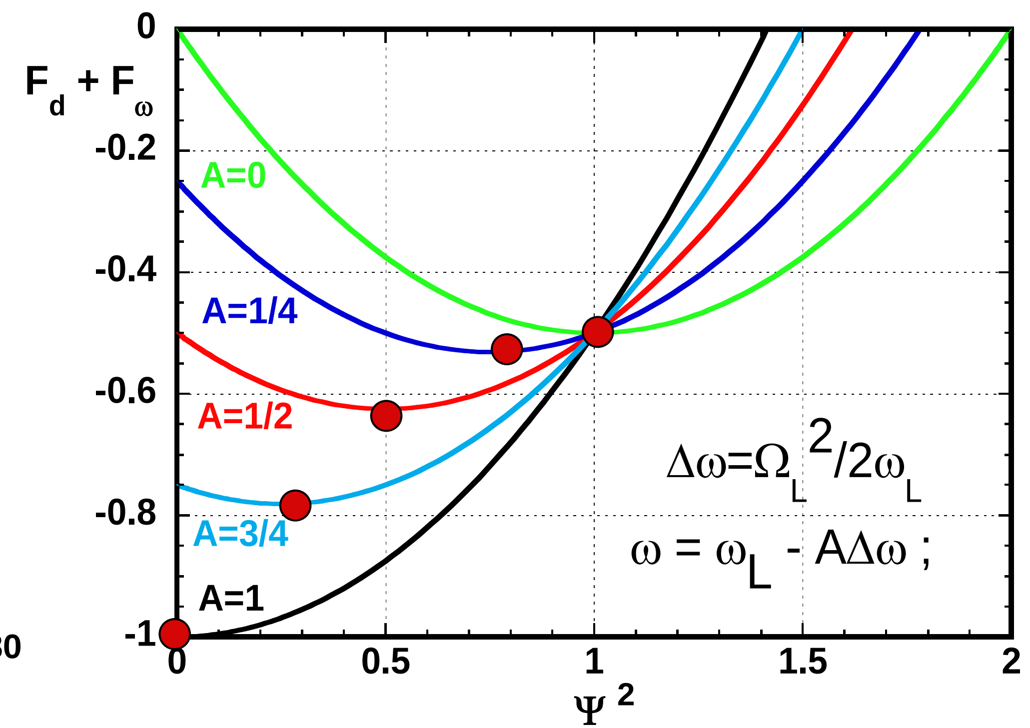


Superfluid ^{3}He-A in squeezed aerogel

$$F = \int d^3r \left(\frac{|\nabla \Psi|^2}{2m_M} + (\omega_L(z) - \omega)|\Psi|^2 + F_D \right)$$

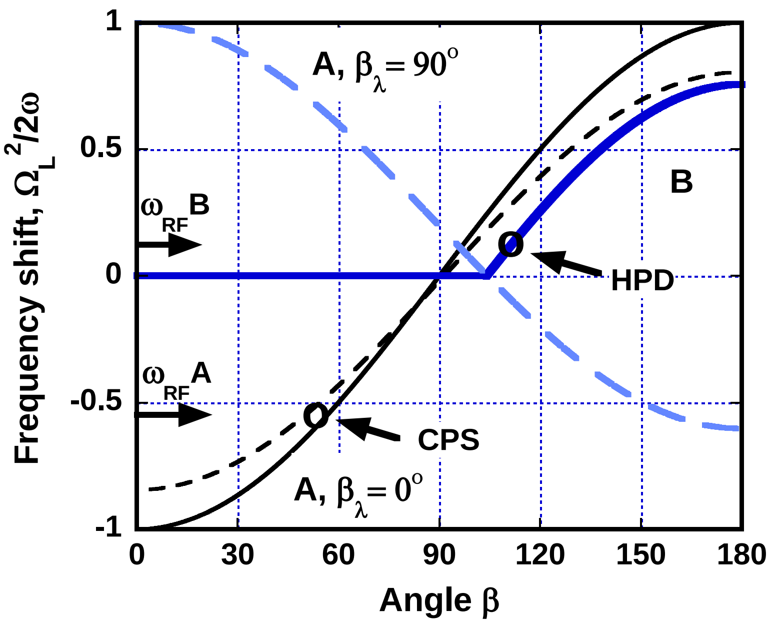
$$F_D = \frac{\chi \Omega_L^2}{4} \left[-2\frac{|\Psi|^2}{S} + \frac{|\Psi|^4}{S^2} + \left(-2 + 4\frac{|\Psi|^2}{S} - \frac{7}{4}\frac{|\Psi|^4}{S^2} \right) \sin^2 \beta_L \right]$$

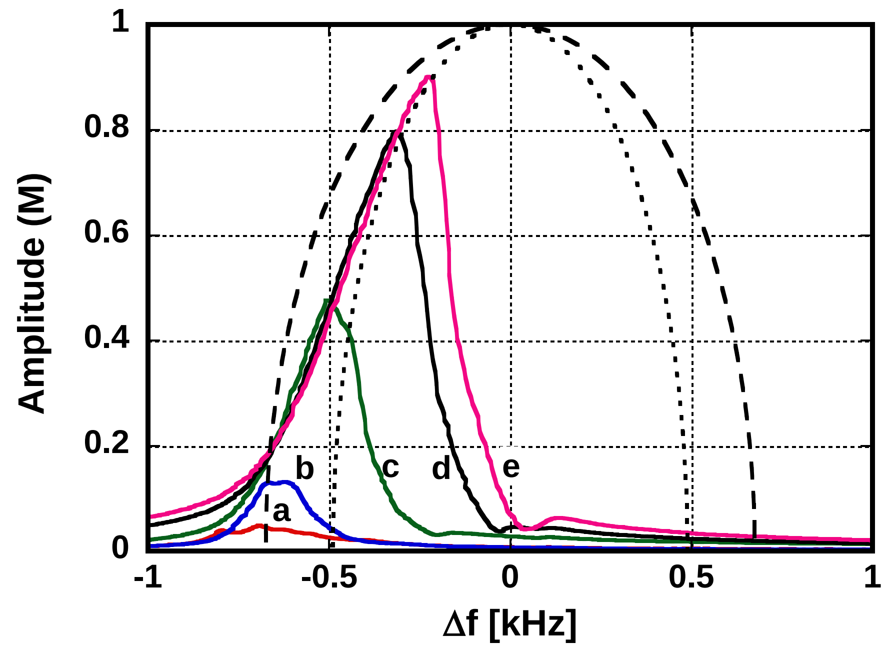


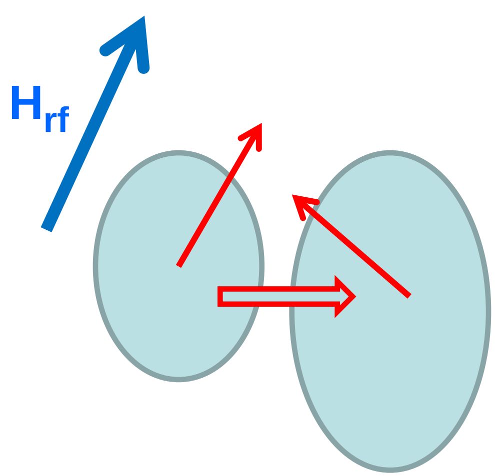


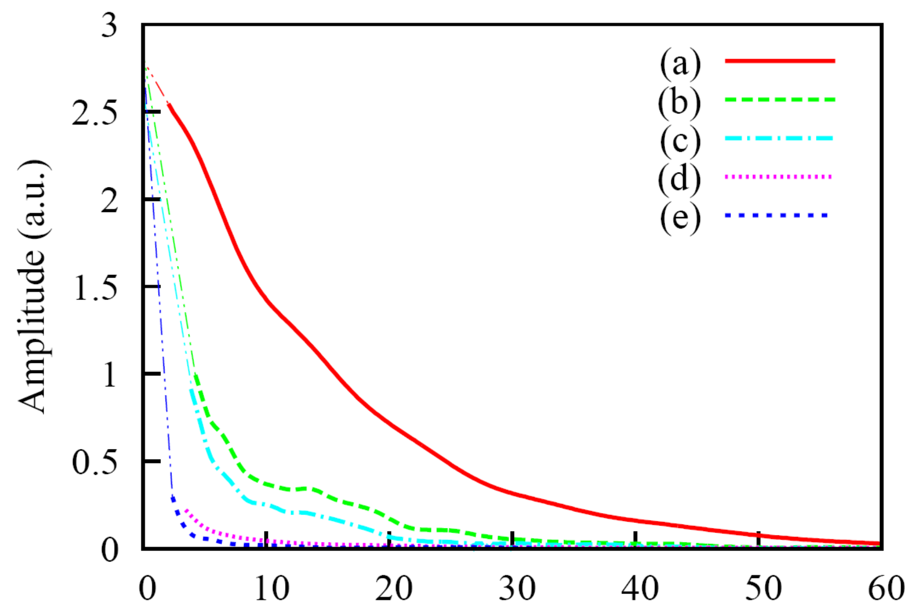
T. Kunimatsu, T. Sato, K. Izumina, A. Matsubara, Y. Sasaki, M. Kubota, O. Ishikawa, T. Mizusaki, Yu.M.Bunkov Pisma v ZhETP, 86, 244 (2007)

T. Sato, T. Kunimatsu, K. Izumina, A. Matsubara, M. Kubota, T. Mizusaki, and Yu.M. Bunkov Phys. Rev. Lett. 101, 055301 (2008)


Frequency shift, Ω_L²/2ω
Angle β
A, β_λ = 90°
A, β_λ = 0°
B
ω_RF B
ω_RF A
HPD
CPS


Amplitude (M)
Δf [kHz]
a
b
c
d
e

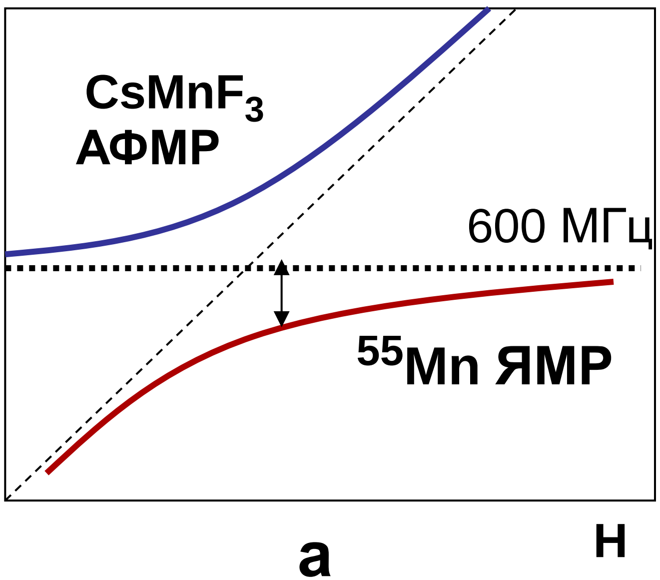

H_rf

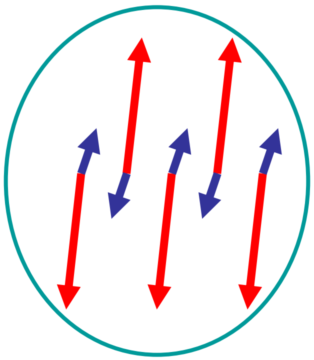

Amplitude (a.u.)
(a)
(b)
(c)
(d)
(e)

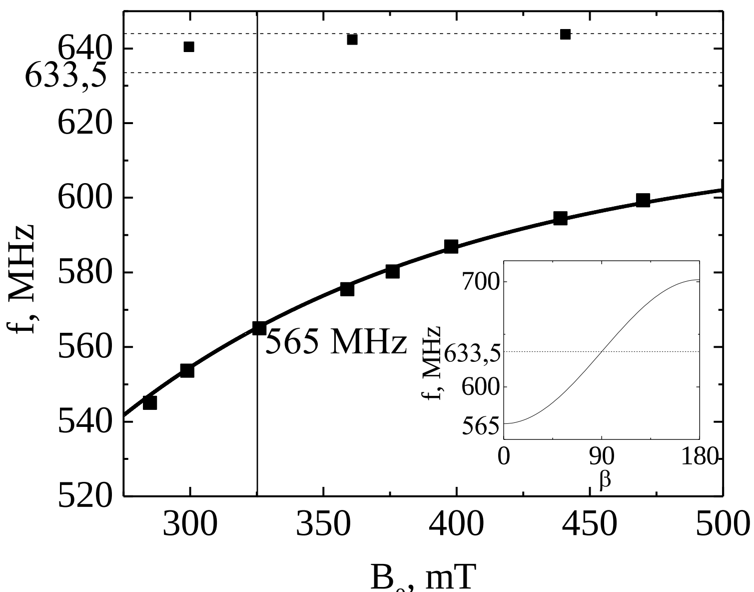
BEC in antiferromagnet with Pulling

Coupled Nuclear electron precession

CsMnF3





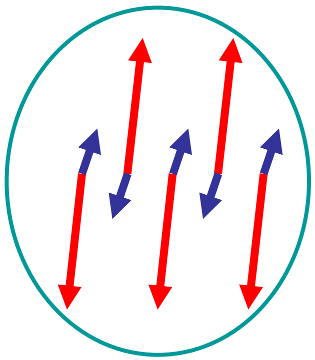


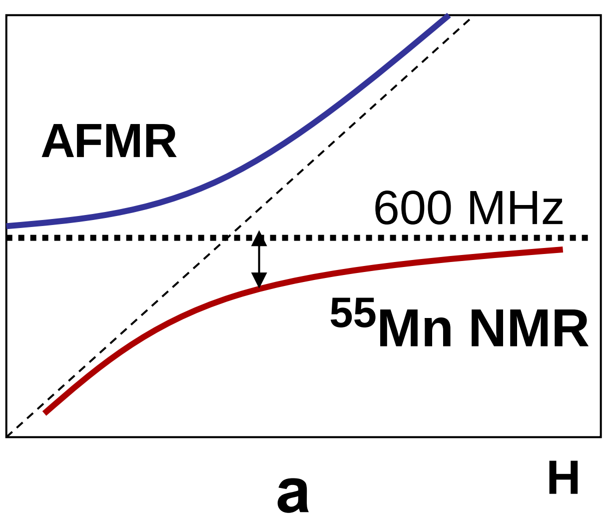
Yu.M. Bunkov, E.M. Alakshin, R.R. Gazizulin, A.V. Klochkov,
V.V. Kuzmin, T.R. Safin, M.S. Tagirov.
« Discovery of the Classical Bose–Einstein Condensation
of Magnons in Solid Antiferromagnets »
JETP Letters, **94**, 68–72 (2011)

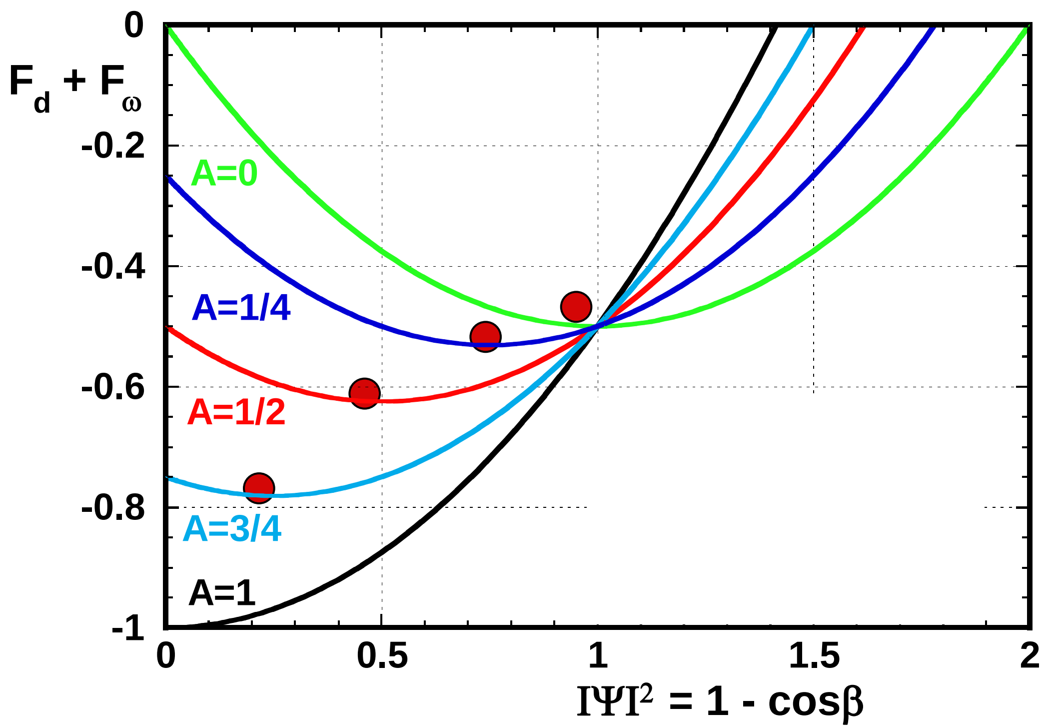
“High Tc spin superfluidity in antiferromagnets”
Yu. M. Bunkov, E.M. Alakshin, R.R. Gazizulin,
A.V. Klochkov, V.V. Kuzmin, V.S. L'vov, and M.S. Tagirov
PRL, Avril 2012.

Suhl – Nacamura interaction

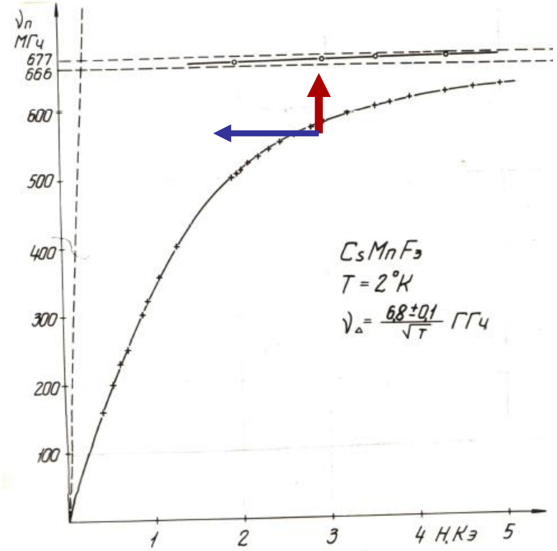
$$F = \int d^3r \left(\frac{|\nabla \Psi|^2}{2m_M} + (\omega_L(z) - \omega)|\Psi|^2 + F_{SN} \right)$$

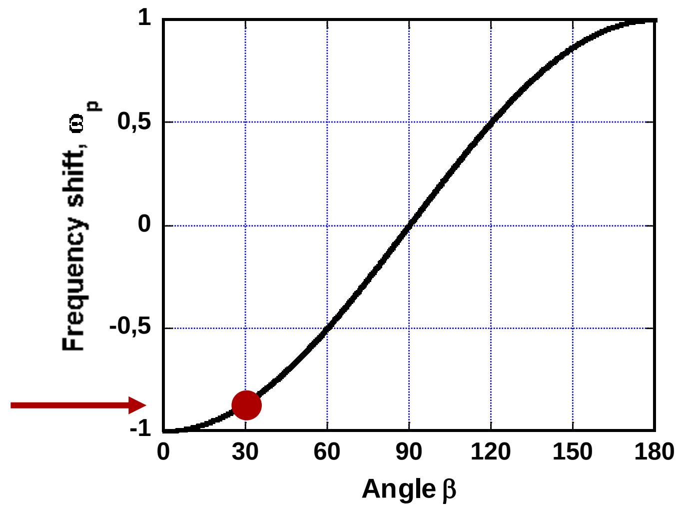




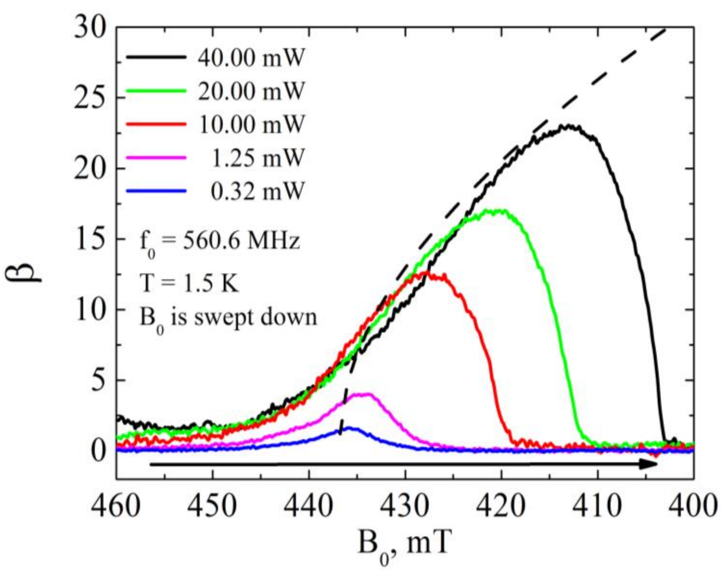


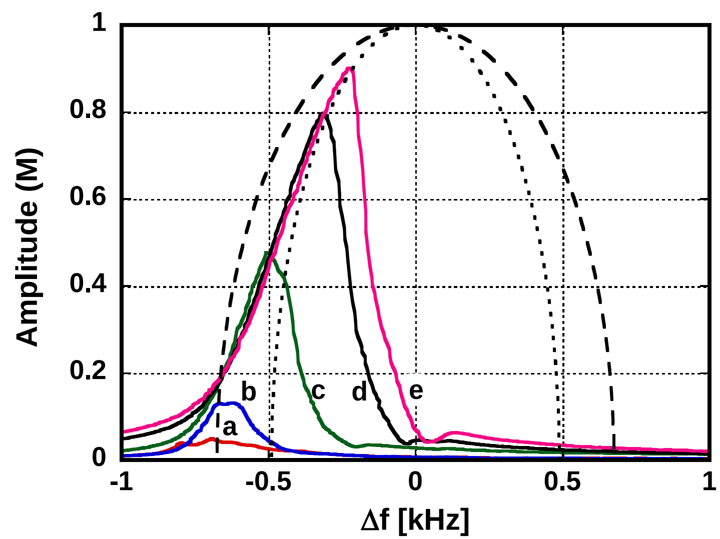
CW NMR experiments





Broadening was about 2 MHz and RF field was only about 300 kHz

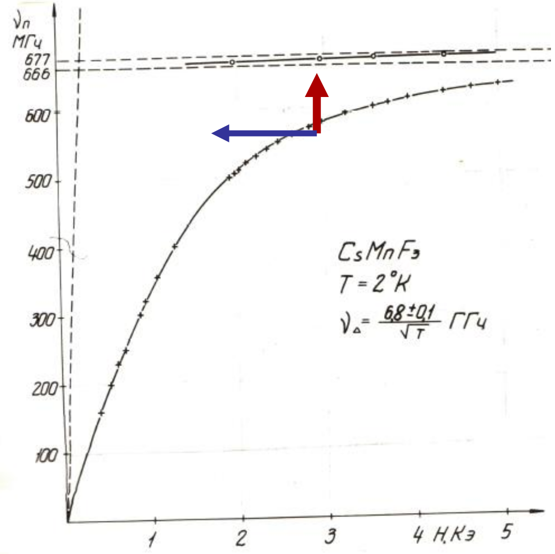


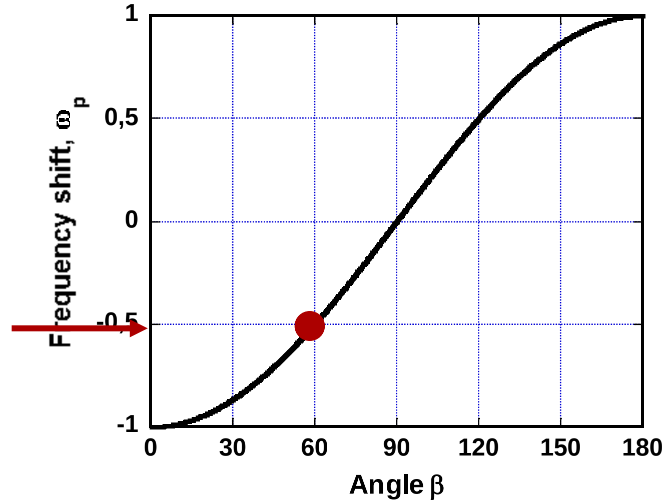


$CsMnF_3$

^{3}He-A in aerogel

CW NMR experiments





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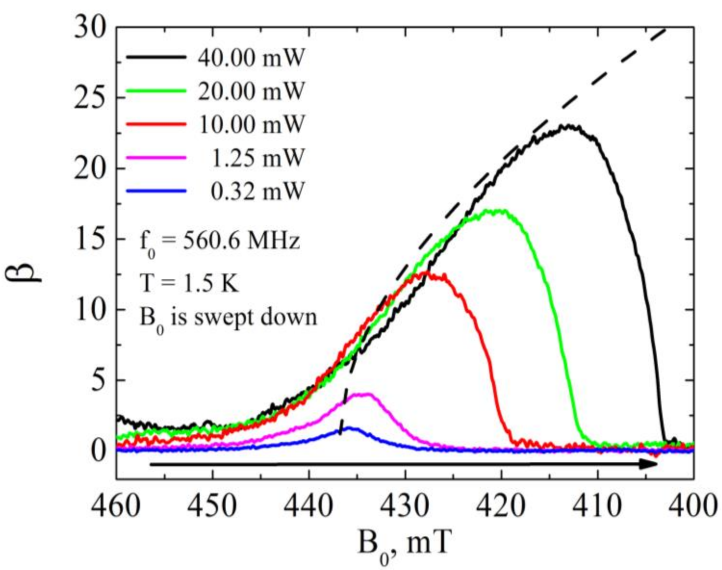
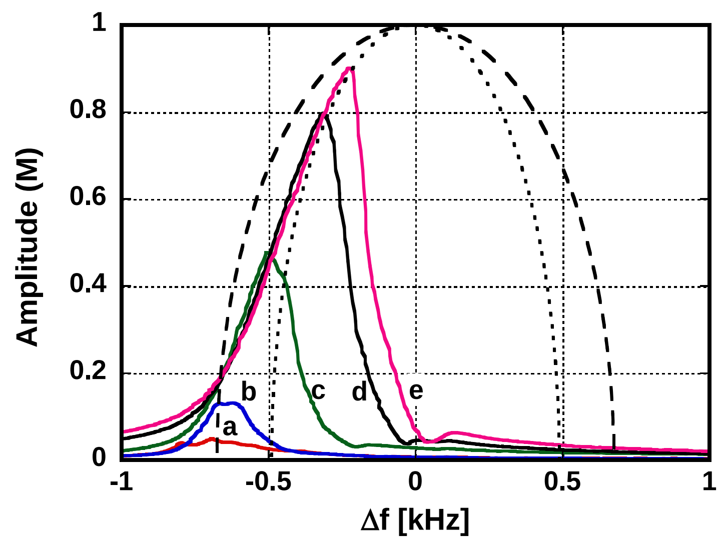
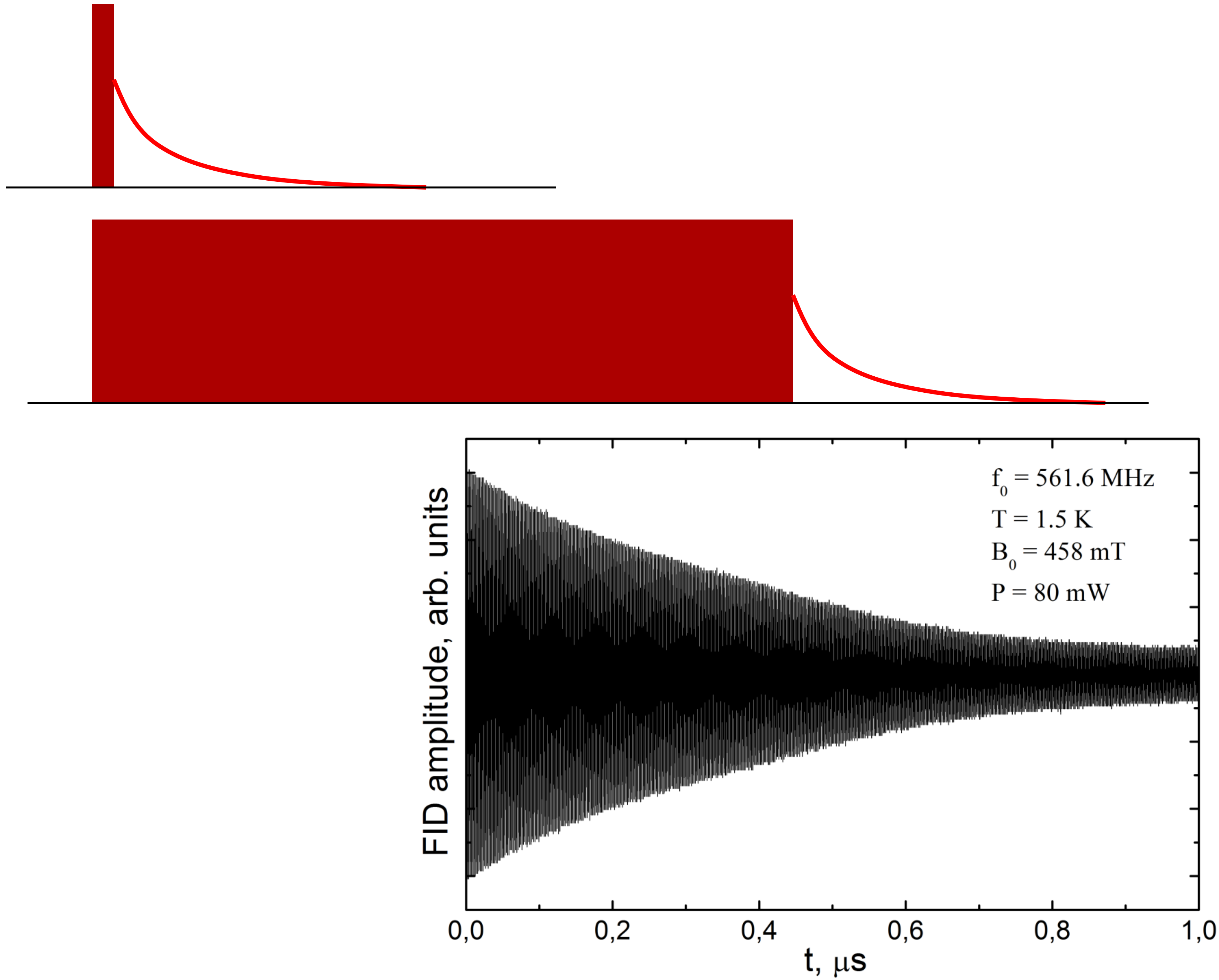


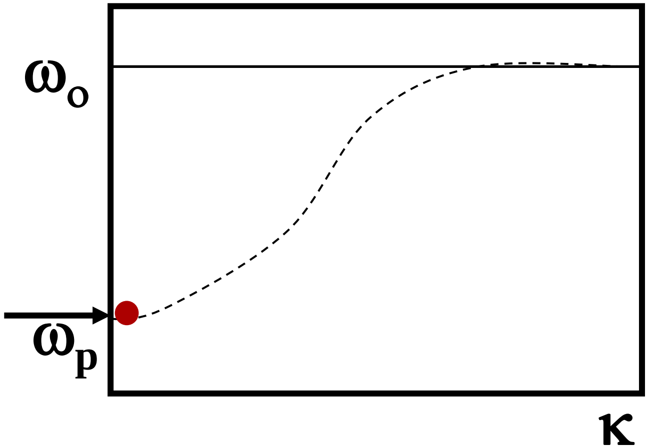


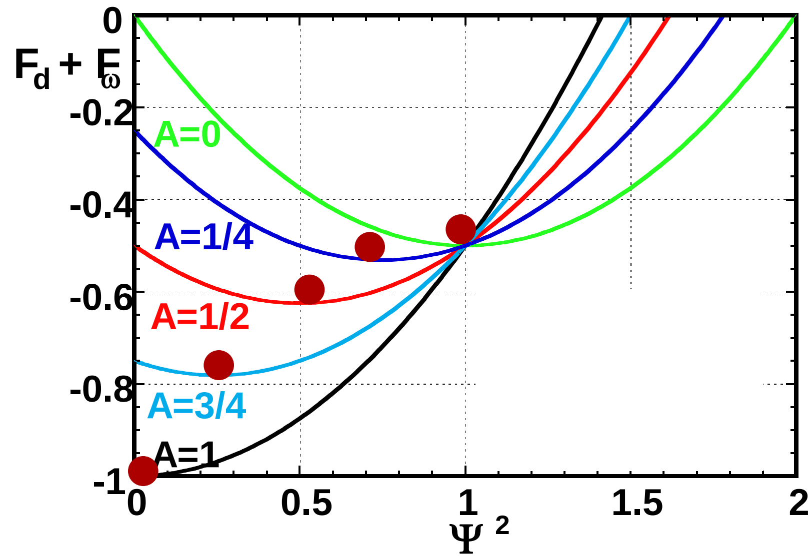
$CsMnF_3$

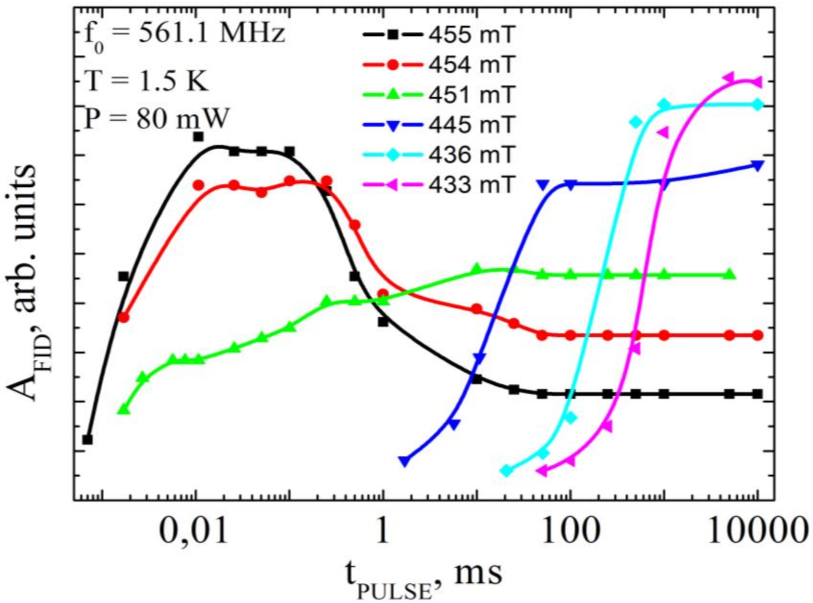
^{3}He-A in aerogel



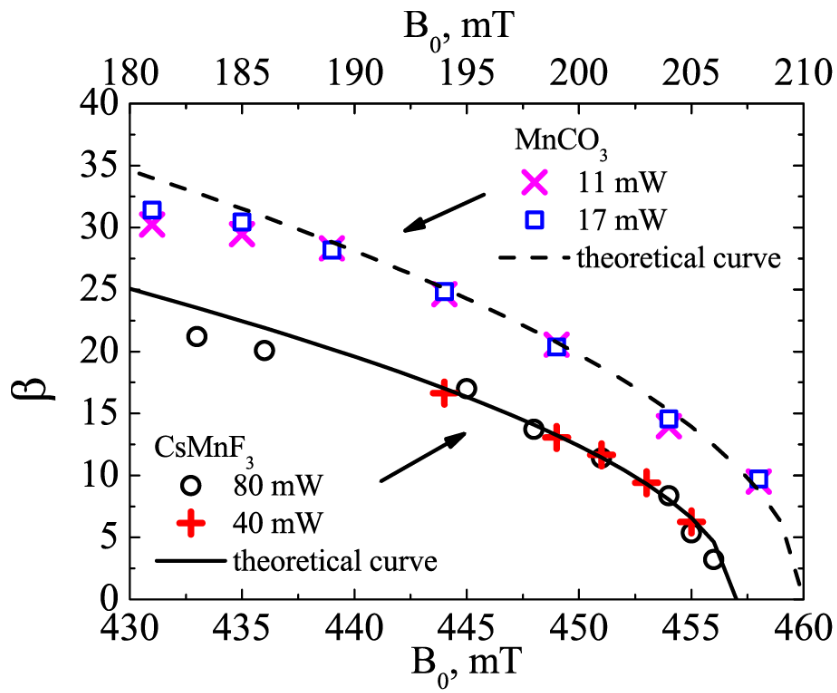
f0 = 561.6 MHz
T = 1.5 K
B0 = 458 mT
P = 80 mW
FID amplitude, arb. units
0,0
0,2
0,4
0,6
0,8
1,0
t, μs



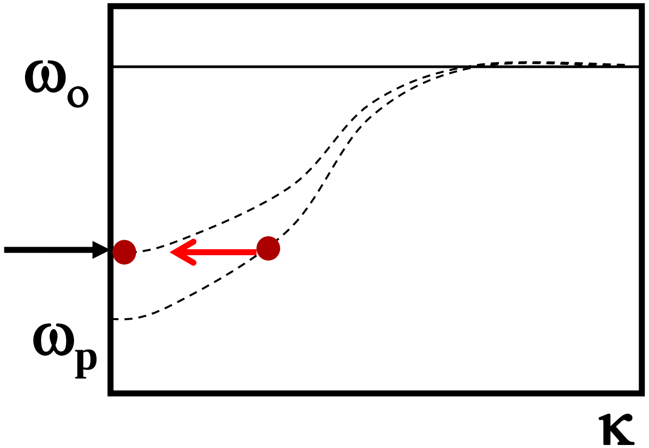


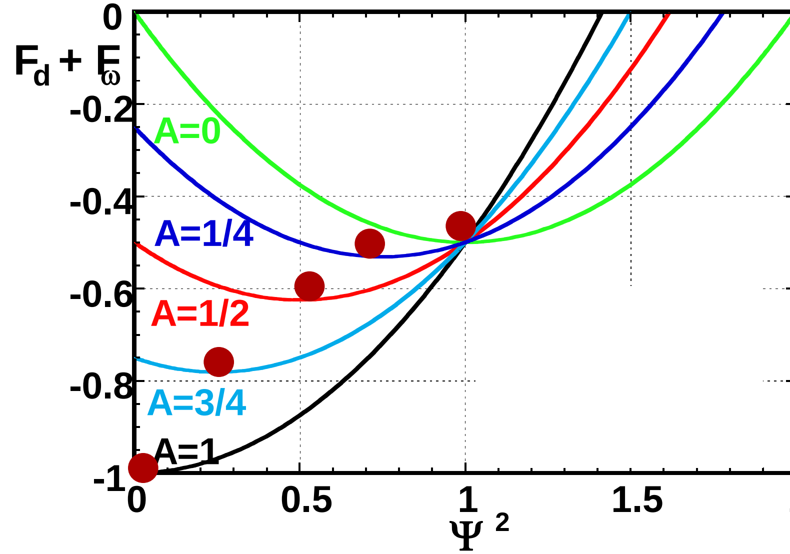


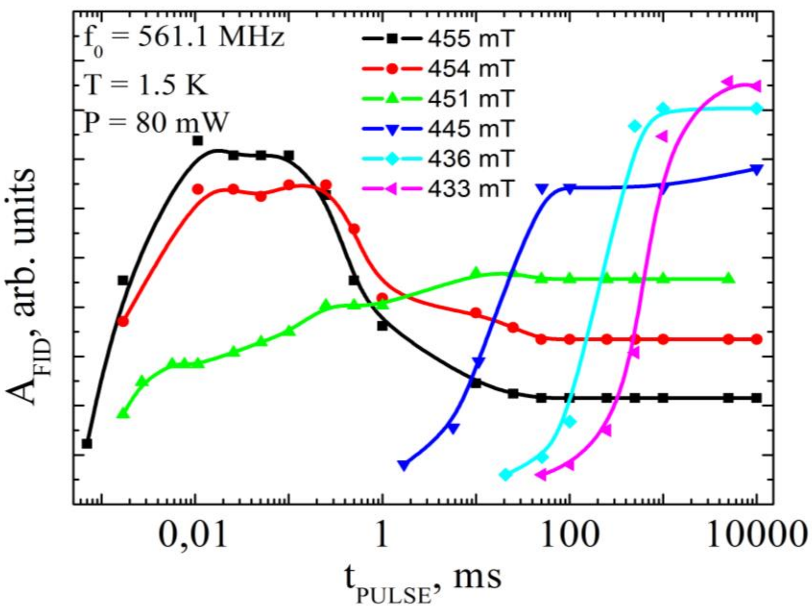
FID amplitude vs. RF pulse length at different magnetic fields



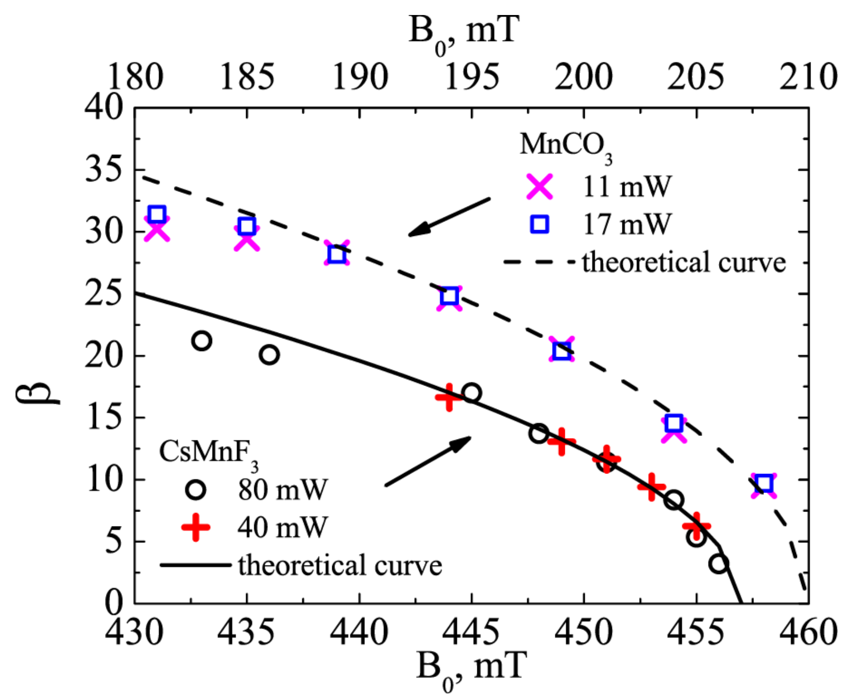
Signal intensity vs. magnetic field





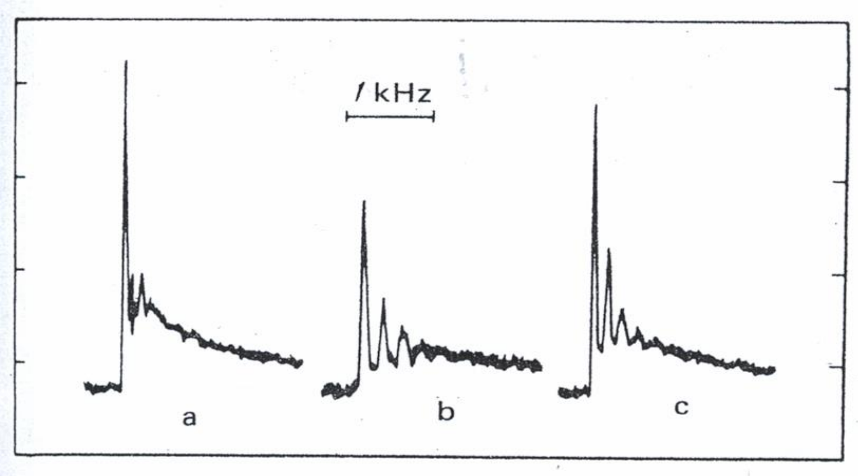


FID amplitude vs. RF pulse length at different magnetic fields



Signal intensity vs. magnetic field

Non-linear Stationary Spin Waves in Flared out texture



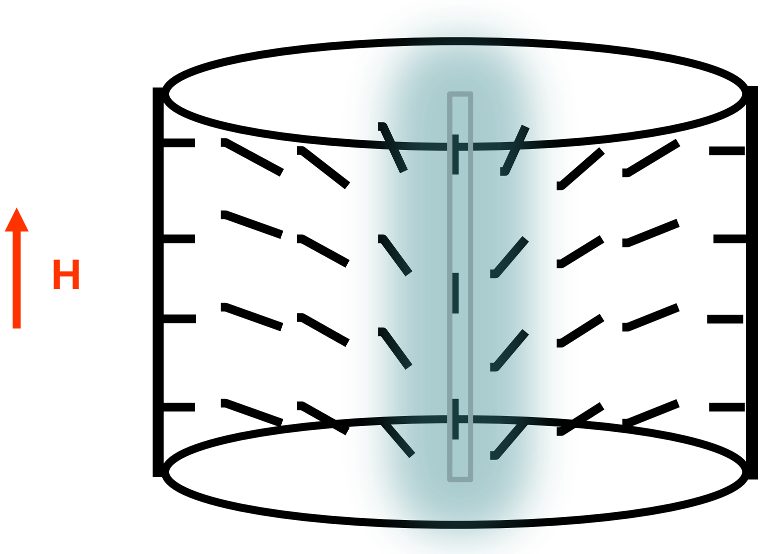
Before rotation During rotation After rotation

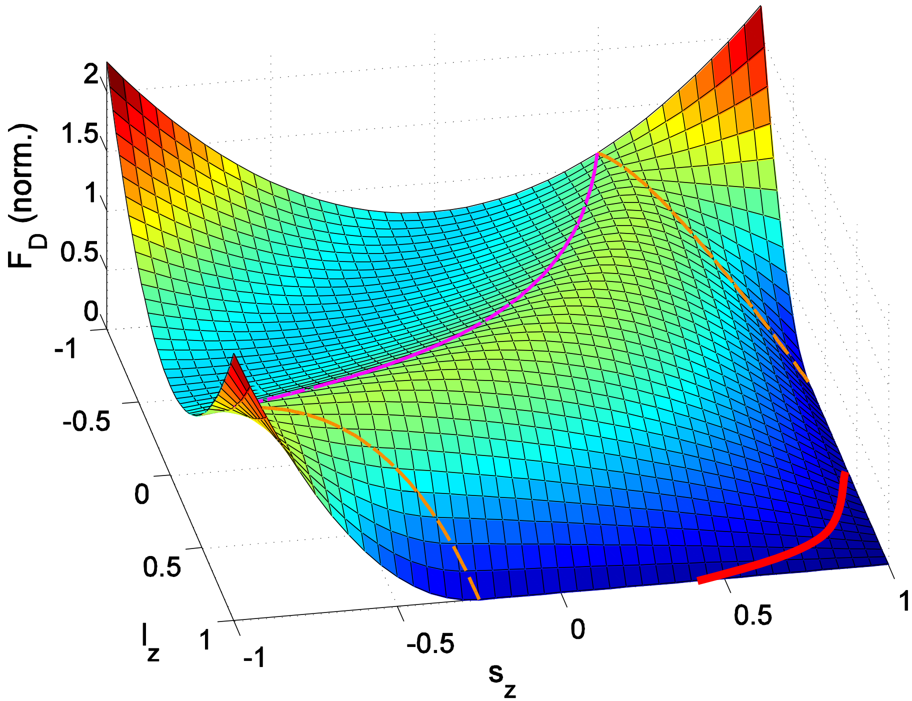
NMR of Rotated superfluid 3He-B

O.T.Ikkala, G.E.Volovik, P.Y.Hakonen, Yu.M.Bunkov, S.T.Islander, G.A.Haradze, JETP Letters v.35, p.416 (1982).

$$\omega^2 = (\gamma H)^2 + n_\perp^2 \Omega_D^2$$

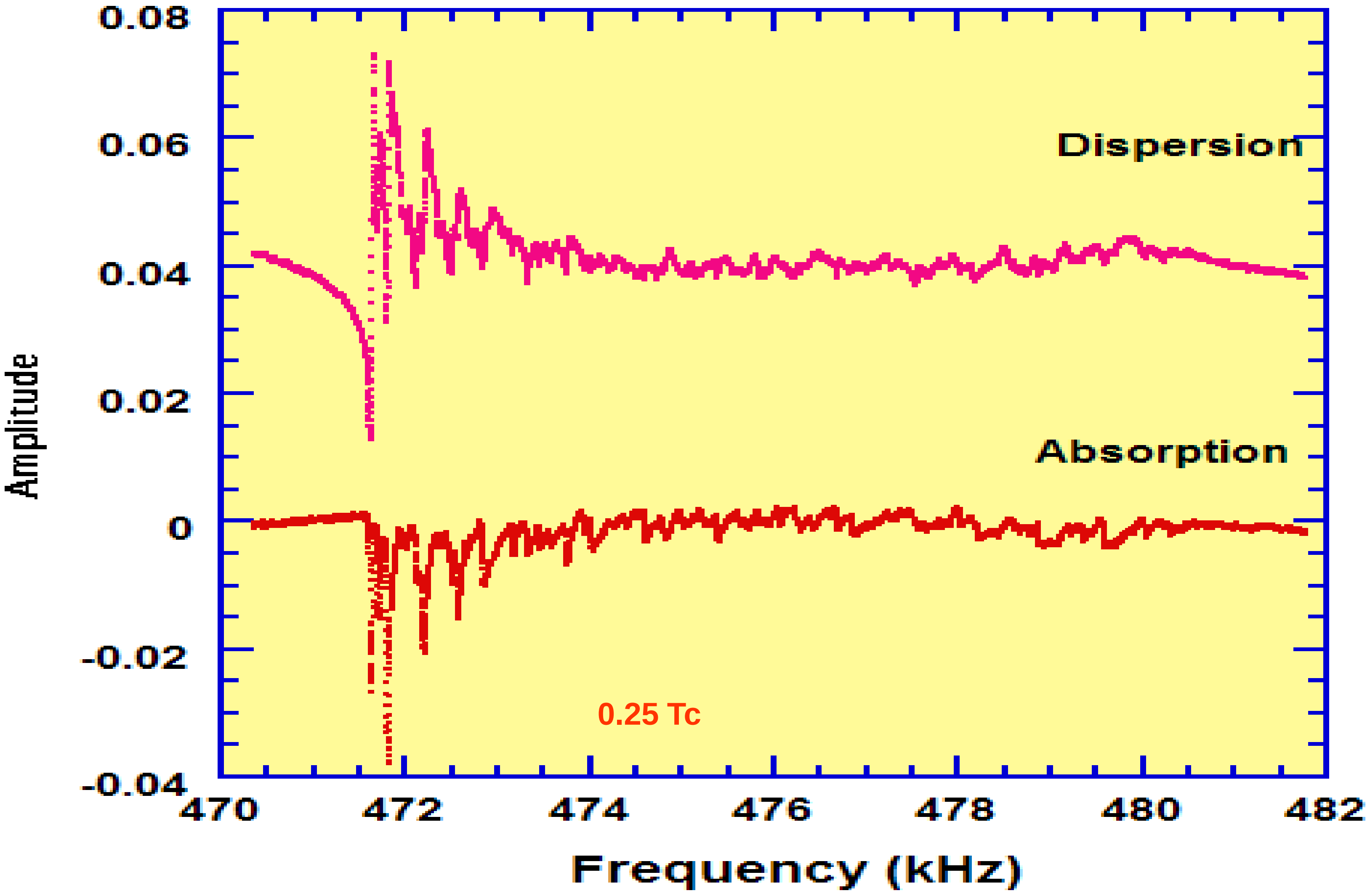
$$(\omega - \omega(z))M^+ = \frac{\Omega_D^2}{2\omega(z)}\left(\frac{2}{5}\sin^2\beta_L(r) - \frac{24}{65}\xi_d^2\nabla^2\right)M^+$$

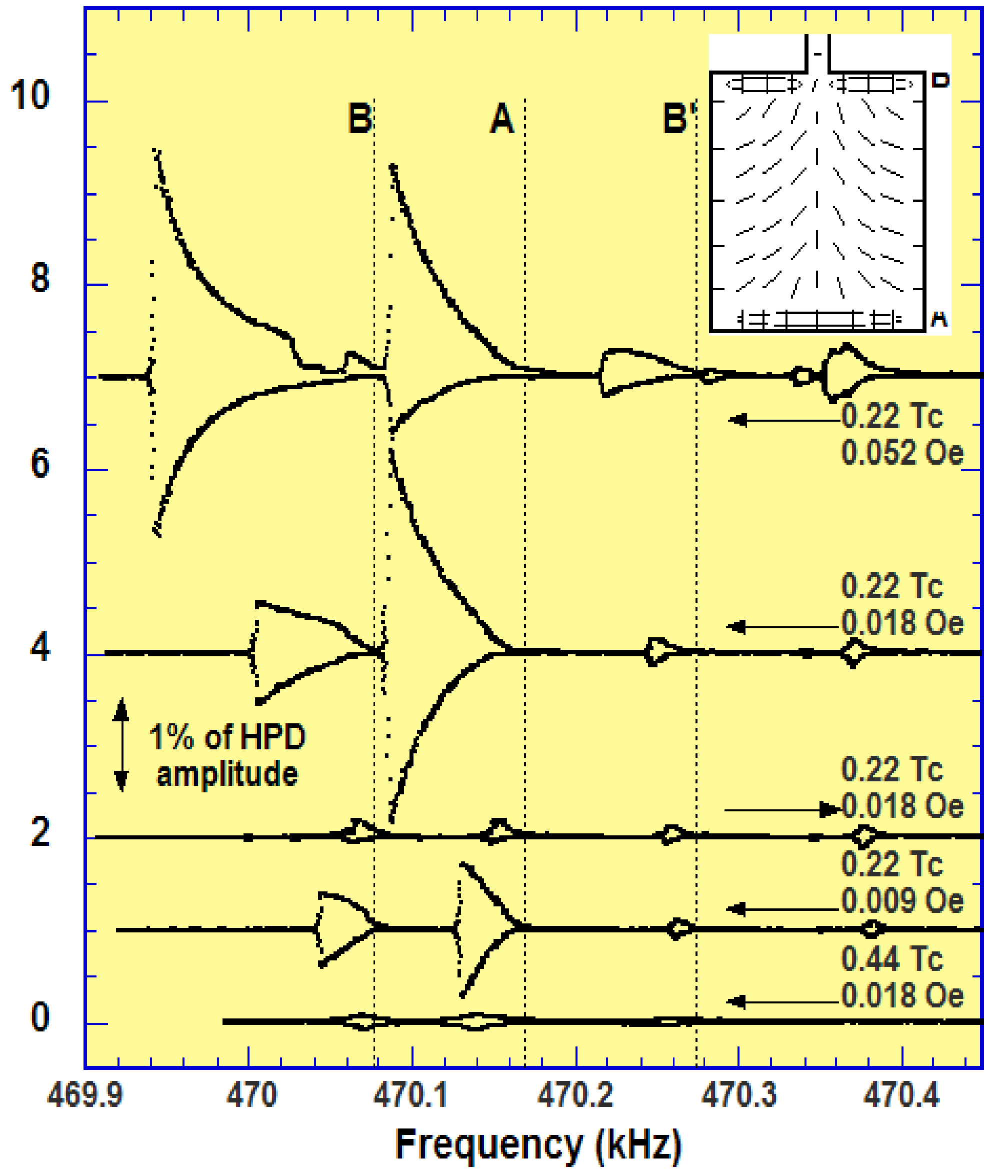


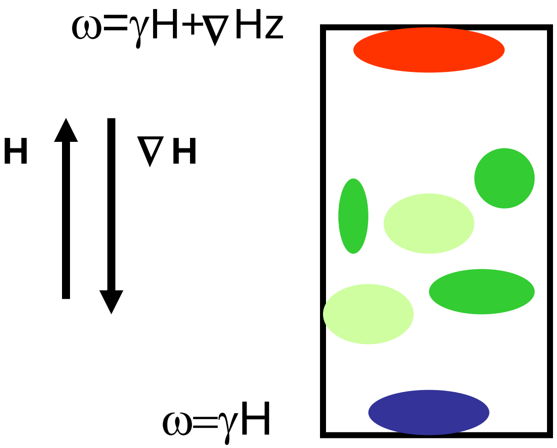


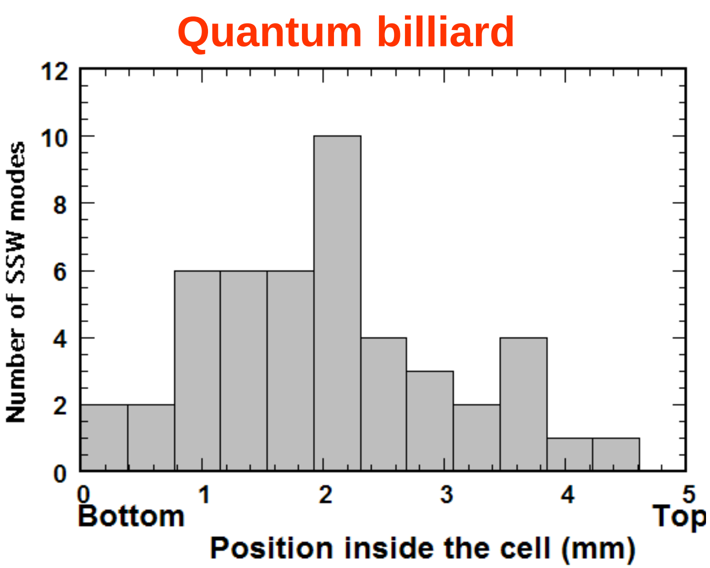
Grenoble experiments with Non-linear Stationary Spin Waves

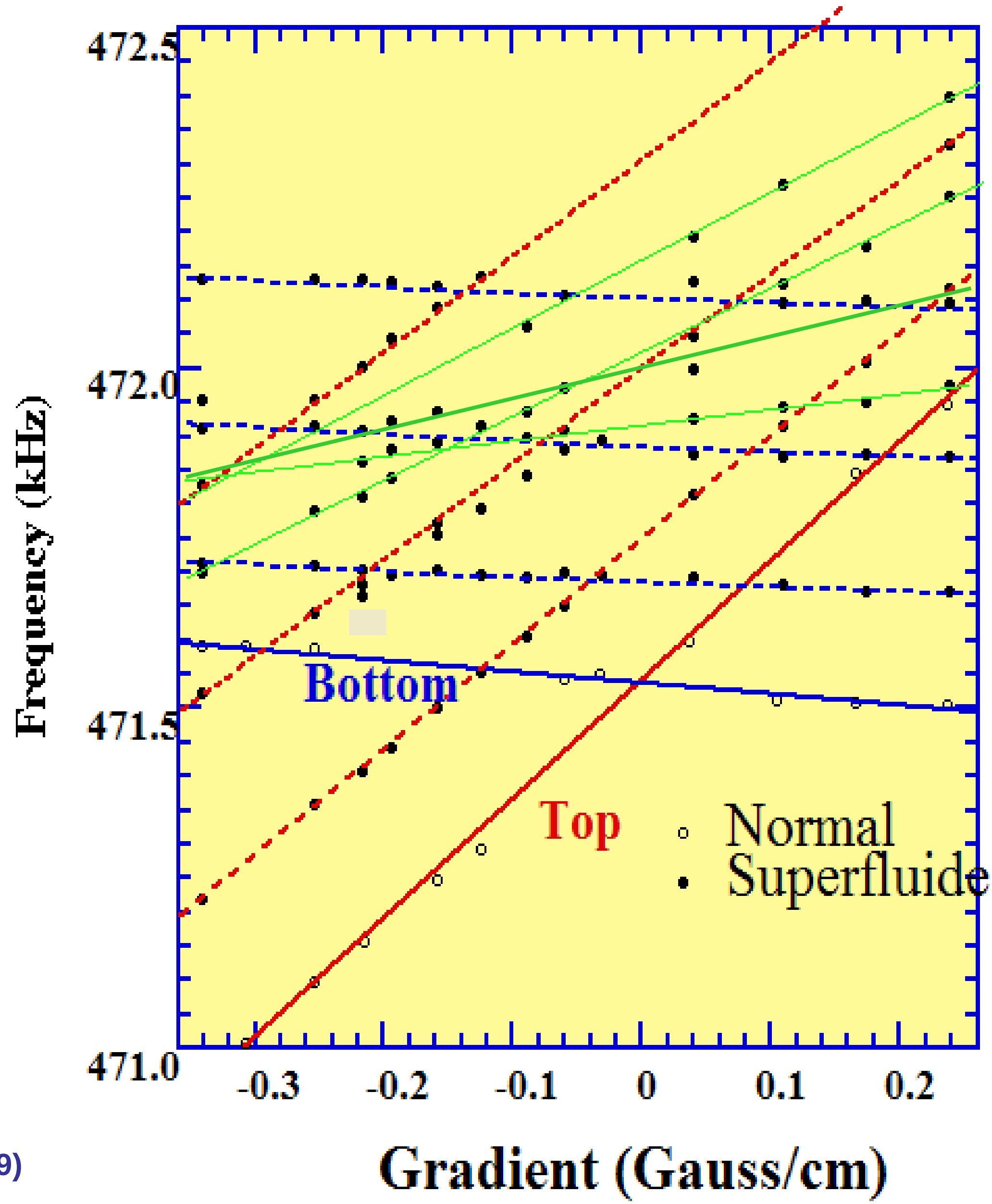
A.-S. Chen, Yu.M. Bunkov, H. Godfrin, R. Schanen, F. Scheffer.
J. Low Temp. Phys, 110, p. 51, (1998).




10
8
6
4
2
0
B
A
B'
0.22 Tc
0.052 Oe
0.22 Tc
0.018 Oe
0.22 Tc
0.018 Oe
0.22 Tc
0.009 Oe
0.44 Tc
0.018 Oe
1% of HPD
amplitude
469.9
470
470.1
470.2
470.3
470.4
Frequency (kHz)

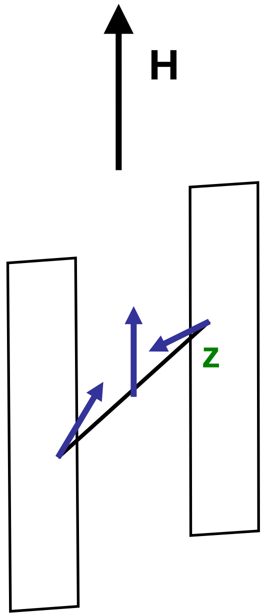






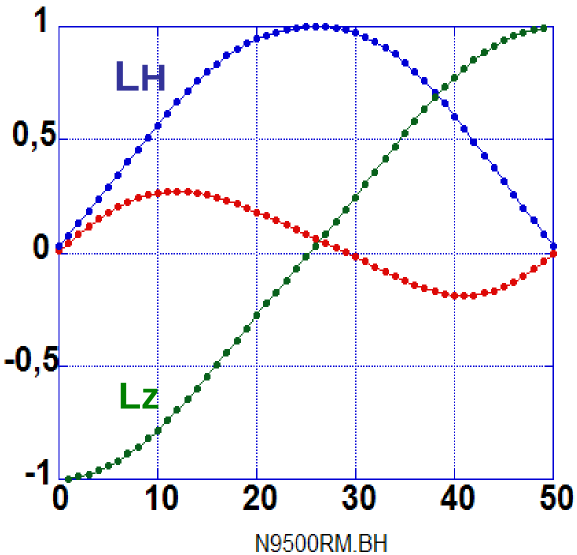
Anne-Sophie CHEN, Ph D Thesis, Grenoble, (1999)

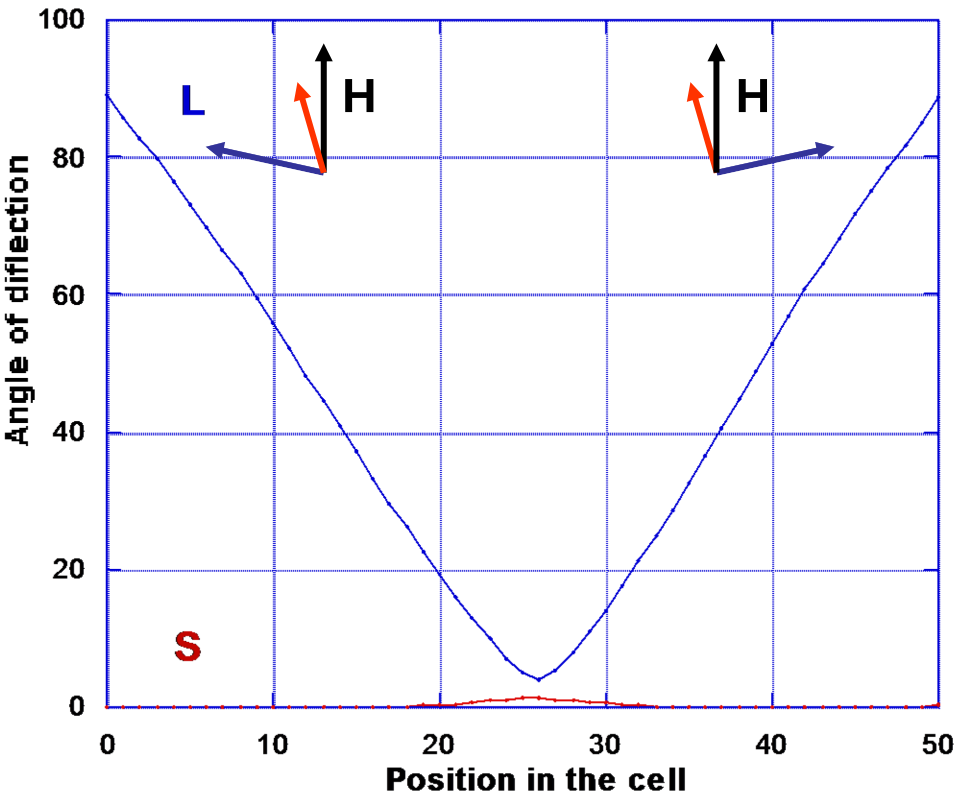
Computer simulation
Grenoble 2004

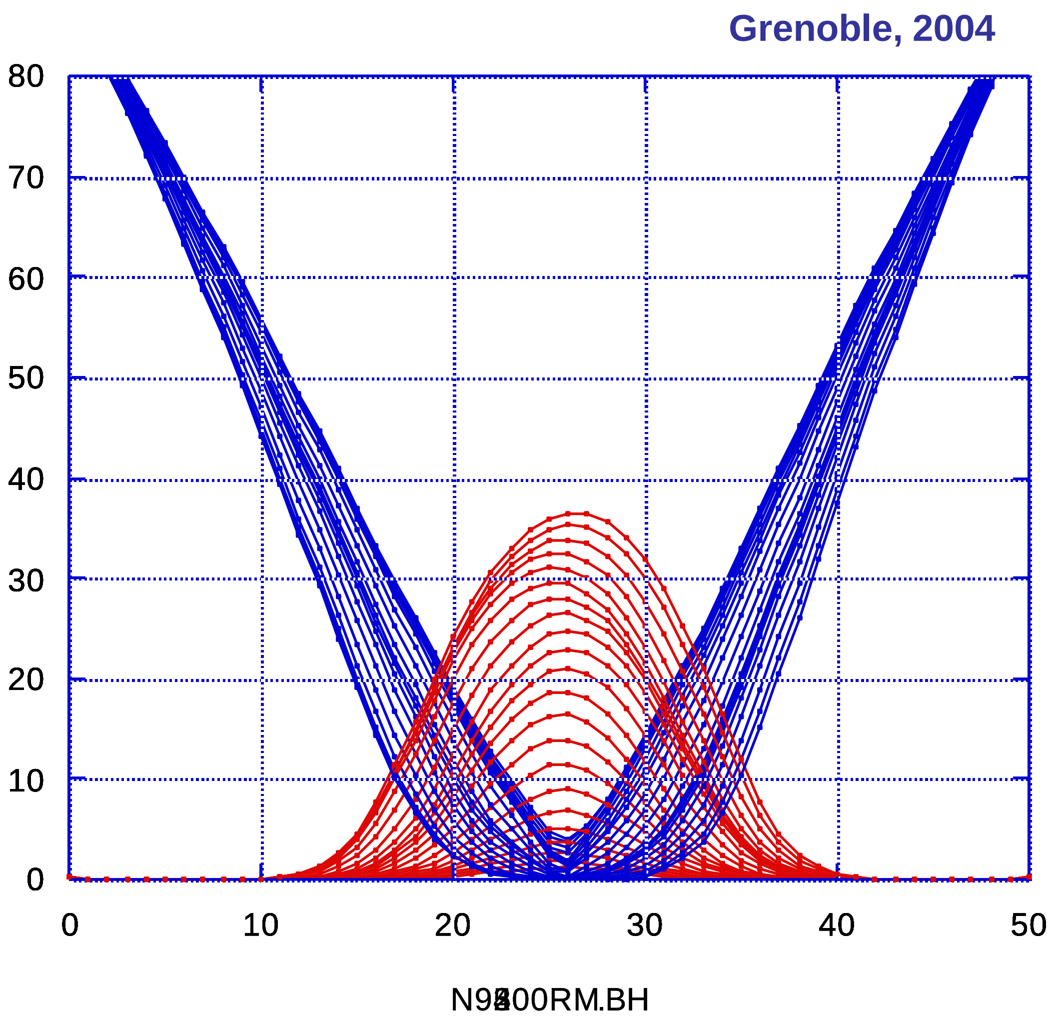


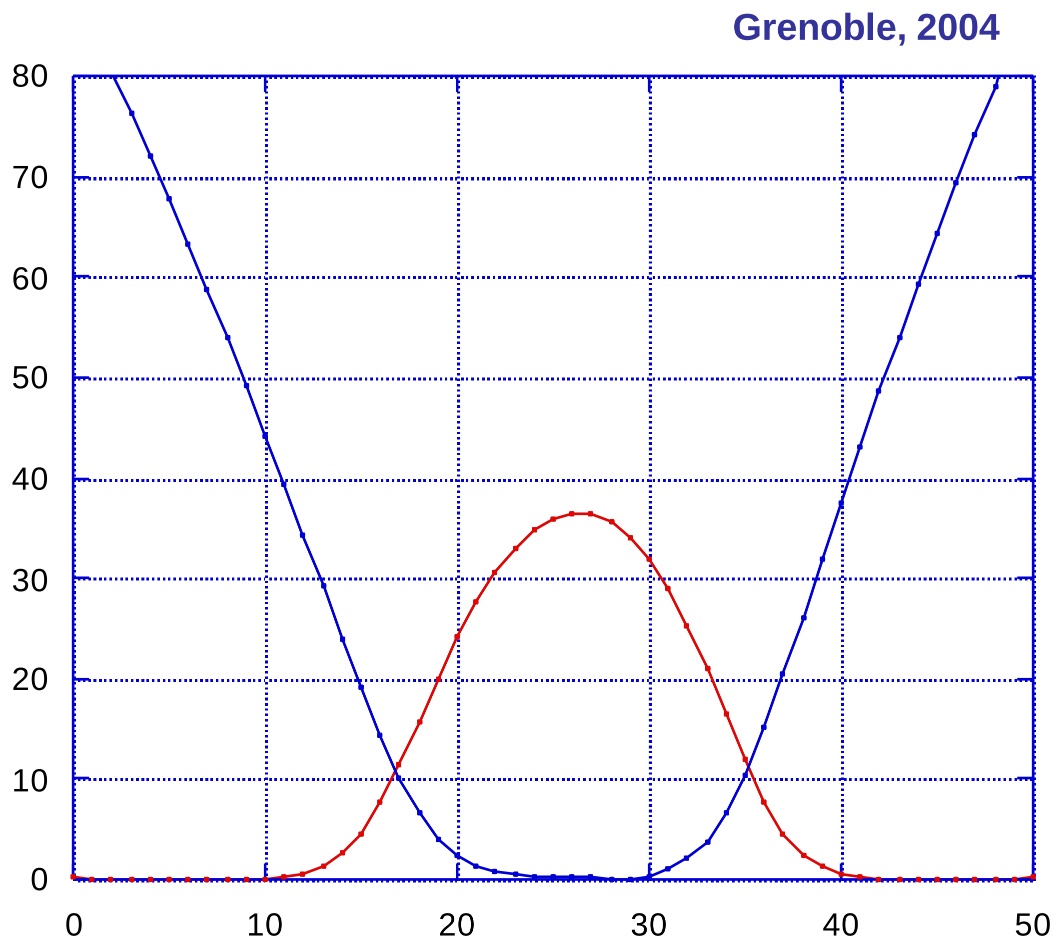
Follow Voislav Golo algorithm

Calculations of a spatial deflection of spin and orbit on basis of Poisson brackets and Takagi relaxation






Grenoble, 2004
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
N94400RM.BH

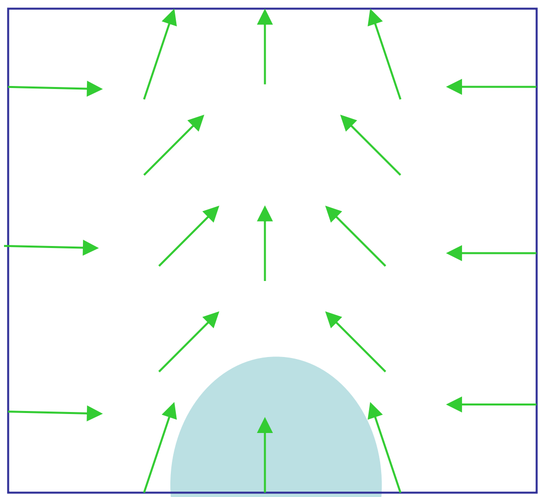

Grenoble, 2004
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50

Magnons condensation in Q-balli In the orbital texture trap

CW NMR A.-S. Chen, Yu.M. Bunkov, H. Godfrin, R. Schanen, F. Scheffer. J. Low Temp. Phys, 110, 51, (1998), 113, 693 (1998).

Yu.M. Bunkov "Persistent Signal; Coherent NMR state Trapped by Orbital Texture" J. Low Temp. Phys, 138, 753 (2005)

Yu.M. Bunkov, G.E. Volovik, *Phys. Rev. Lett.*, 98, 265302 (2007).



3D axisymmetric trap.

$\omega_{xy}{}^2 r^2 + \omega_z{}^2 z^2$

$$F_D = \chi\Omega_L^2 \left[\frac{4\sin^2(\beta_L/2)}{5S} |\Psi|^2 - \frac{\sin^4(\beta_L/2)}{S^2} |\Psi|^4 \right]$$

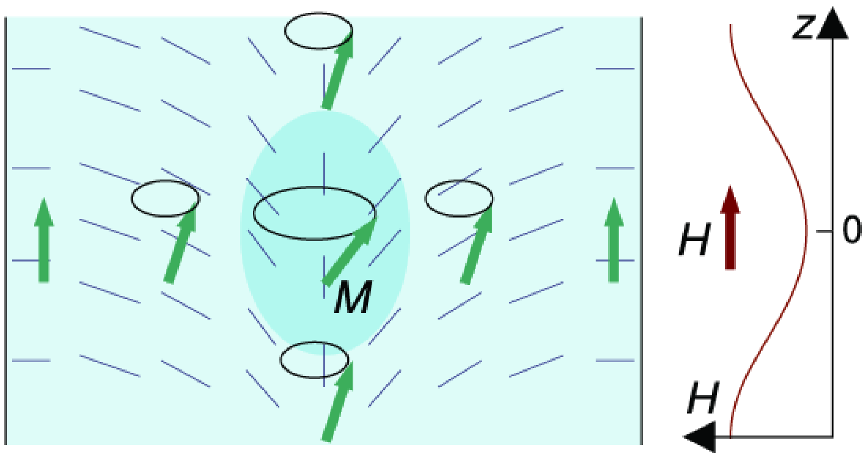
$$Q \sim |\Psi|^2 r_Q^2 l_Q,$$

$$U(r,z) \propto \kappa^2 r^2 z^2 / (r^2 + z^2).$$

$$(\omega - \omega_L(z))\Psi = \frac{\delta F}{\delta \Psi^*},$$

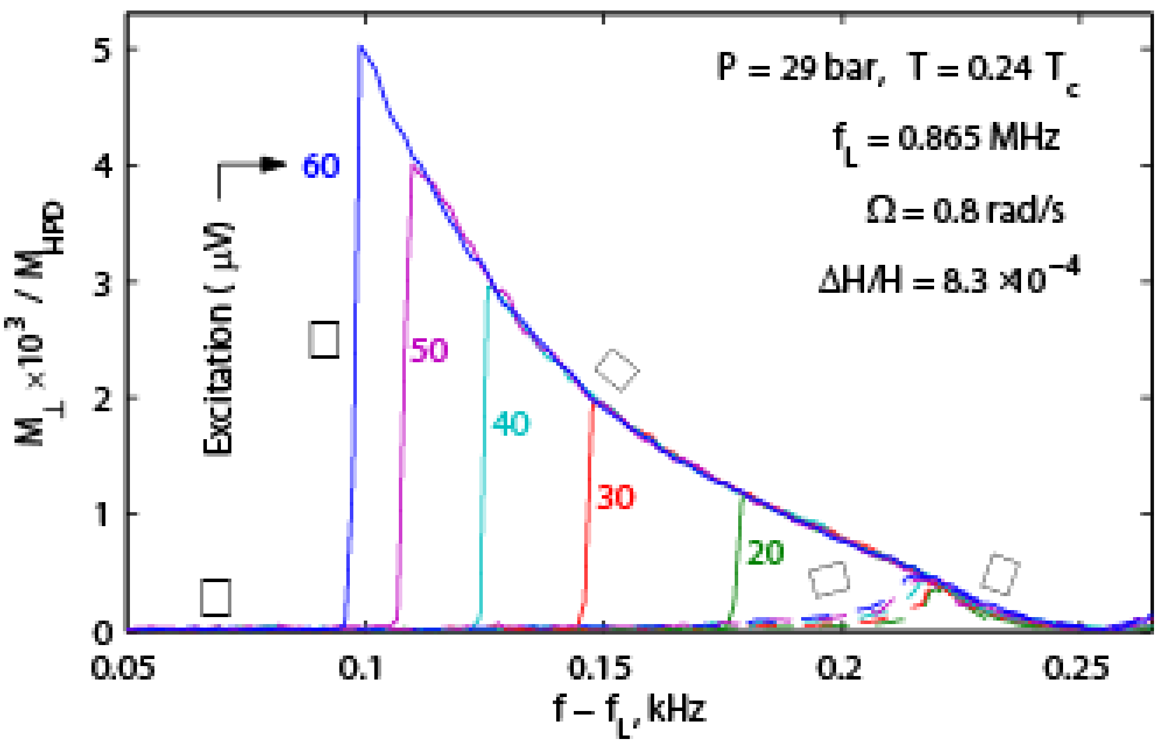
$$F = \int d^3r \left(\frac{|\nabla\Psi|^2}{2m_M} + F_D \right),$$

Non-ground-state Bose-Einstein condensates of magnons in superfluid 3He-B



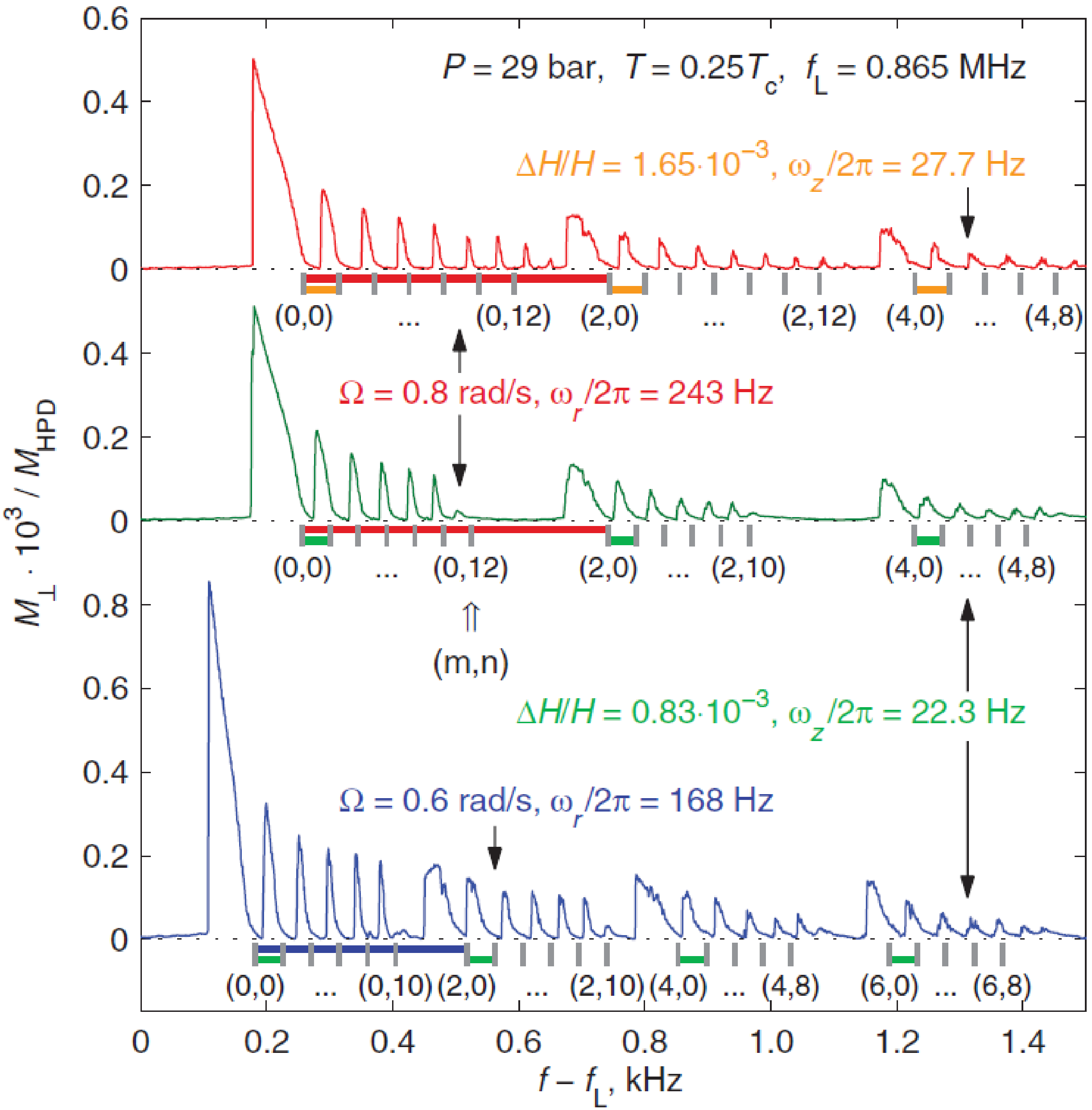
3D axisymmetric trap.

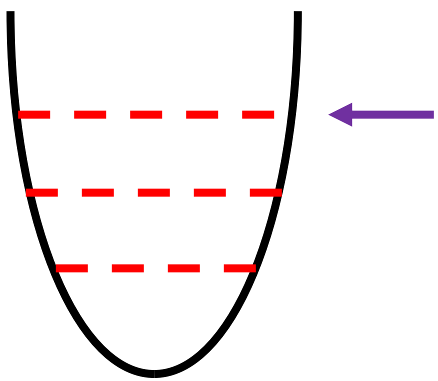
$$\omega_{xy}^2 r^2 + \omega_z^2 z^2$$

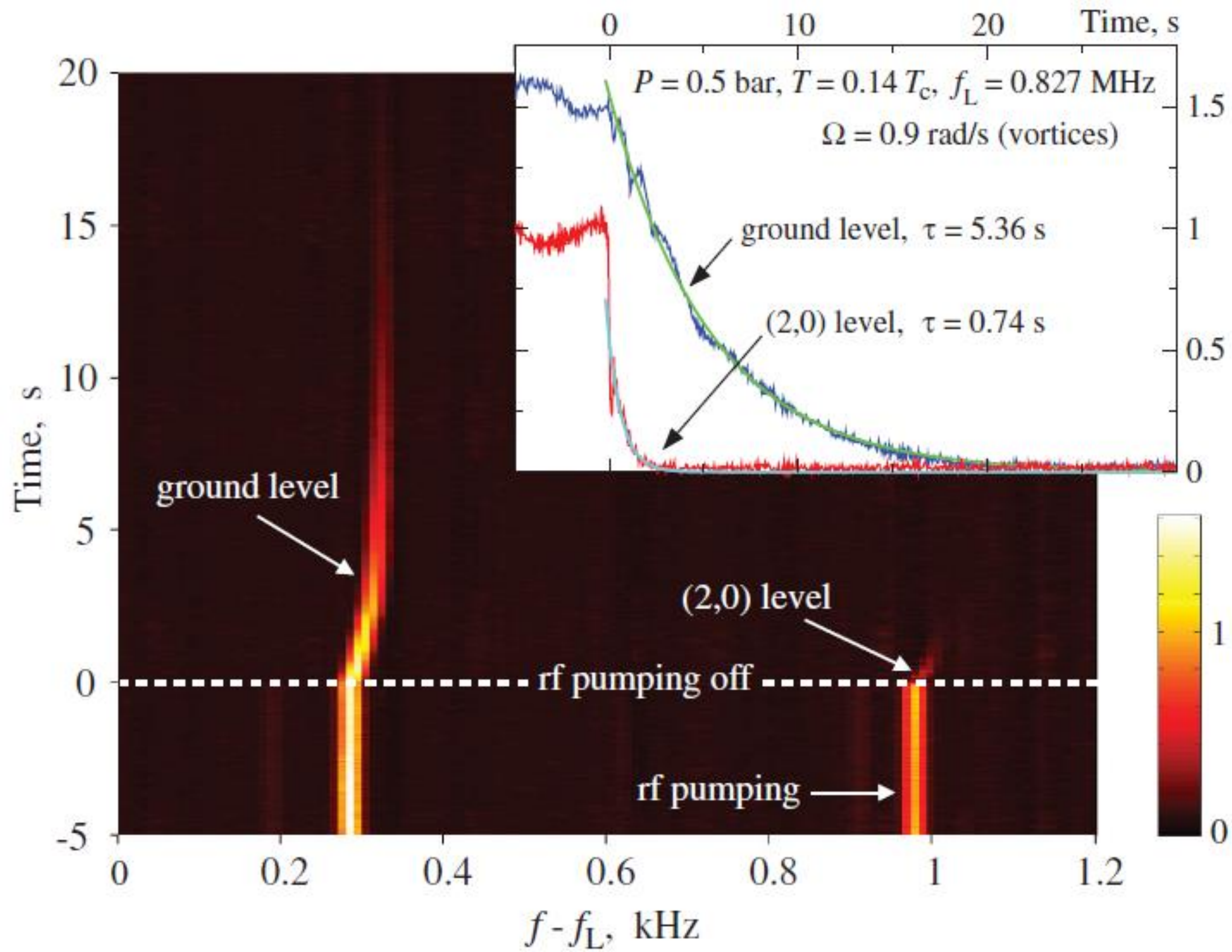


Non-ground-state Bose-Einstein condensates of magnons in superfluid 3He-B

$$f - f_0 = a_r(\Omega)(2n_r + 1) + a_z(2n_z + 1/2),$$







Time, s
0
10
20
P = 0.5 bar, T = 0.14 T_c, f_L = 0.827 MHz
Ω = 0.9 rad/s (vortices)
ground level, τ = 5.36 s
(2,0) level, τ = 0.74 s
1.5
1
0.5
0
20
15
10
5
0
-5
Time, s
ground level
(2,0) level
rf pumping off
rf pumping
0
0.2
0.4
0.6
0.8
1
1.2
f - f_L, kHz
1
0

Conclusions

The Spin Superfluidity, the magnetic counterpart of mass superfluidity and electric supercondactivity was discovered and widely studied in Moscow, Grenoble, Lancaster, Ithaca, Helsinki, Kosice, Kyoto, Tokio, Los-Alamos and by many theoreticians.

There was discovered and observed:

1. The coherent transport of magnetization in superfluid 3He-B.
2. Its based only on an antiferromagnetic properties of 3He and can be found
in other magnetically ordered materials.
3. The formation of domain with coherent precession of magnetization.
4. This excited state correspond to a Bose-Einstein Condensation of spin waves.
5. Josephson phenomena, critical current and phase slippage in a channel.
5. Different modes of HPD oscillations.
6. Horizontal and vertical Spin vortex.
7. HPD techniques was applied for studies of counterflow and mass vortices in
   3He, new types of vortex - spin-mass vortex was observed
8. 6 different states with coherent precession in A and B phases of 3He
9. Magon BEC was found recently in JYG. (Demokritov) *Nature* 443, 430 (2006).


The end
オキちゃん劇場