

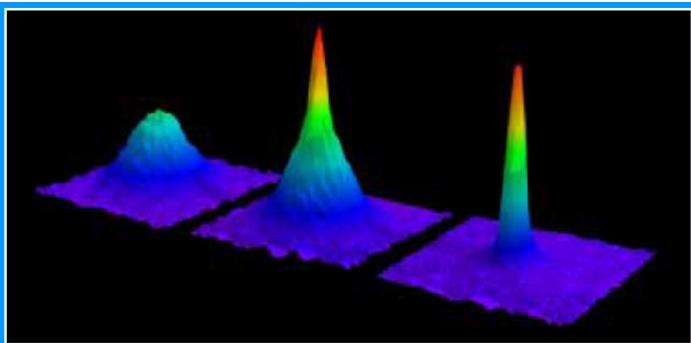
Magnon BEC, new results.

Yu.M. Bunkov
Institut Neel, France



Kazan, 28.10.2013

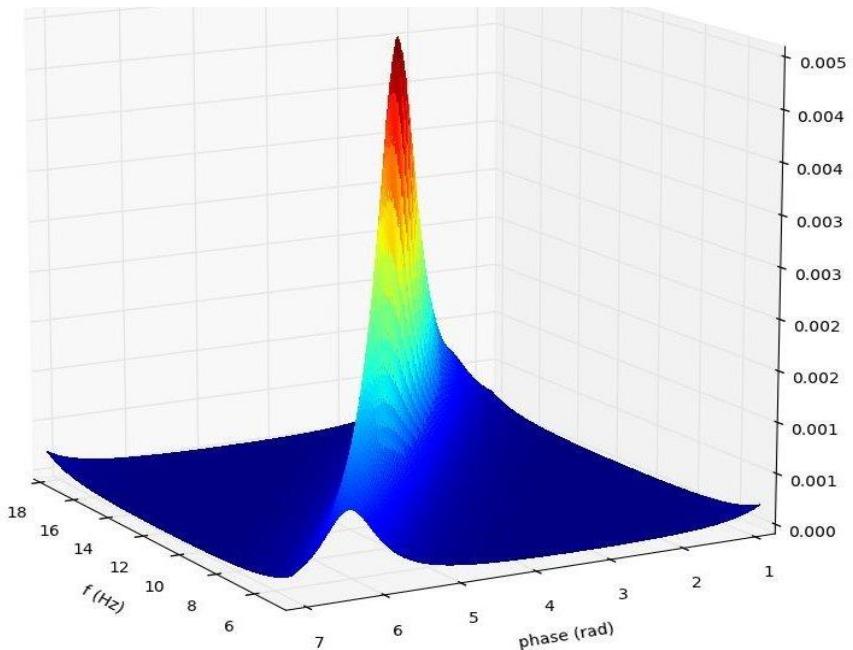
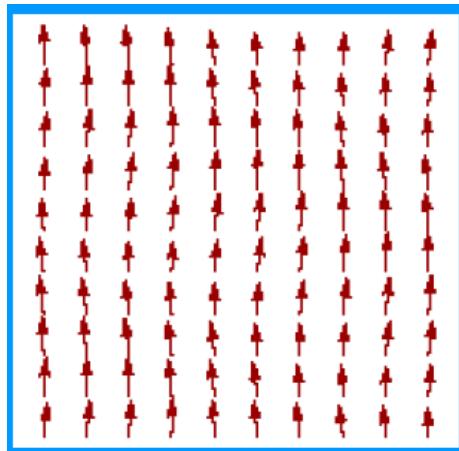


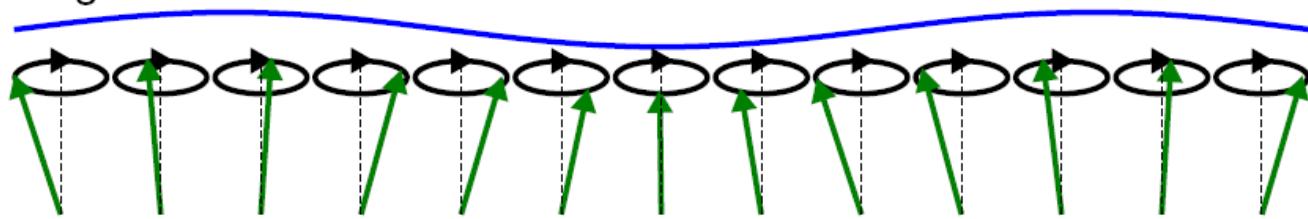


Atomic BEC

BEC of spin waves
In superfluid $^3\text{He-B}$

Magnetically ordered states





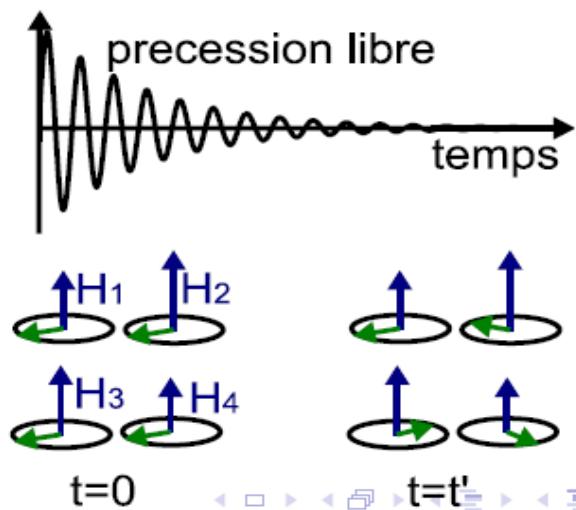
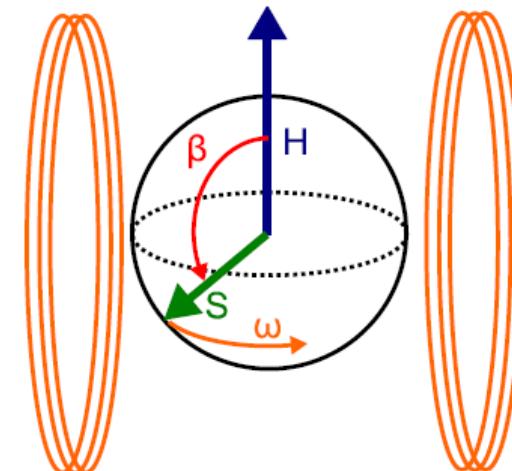
Holstein-Primakoff transformation

$$\begin{cases} \hat{S}_+ = \sqrt{2S\hbar}\hat{a}_0\sqrt{1 - \frac{\hbar\hat{a}_0^\dagger\hat{a}_0}{2S}} \\ \hat{S}_- = \sqrt{2S\hbar}\sqrt{1 - \frac{\hbar\hat{a}_0^\dagger\hat{a}_0}{2S}}\hat{a}_0^\dagger \\ \hat{S}_z = S - \hbar\hat{a}_0^\dagger\hat{a}_0 = S - \hbar\hat{N}_0 \end{cases}$$

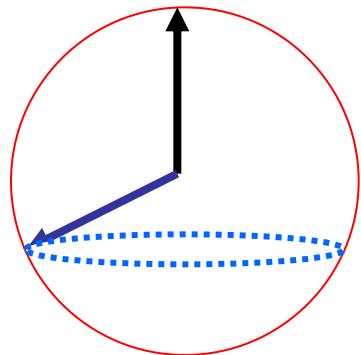
Thermalised magnons
Excited magnons
Coherent magnons

Bloch
equations
 $\Delta\omega$, T2, T1

~~$$\begin{aligned} \frac{dM_x}{dt} &= \gamma M_y B_o - \frac{M_x}{T_2} \\ \frac{dM_y}{dt} &= -\gamma M_x B_o - \frac{M_y}{T_2} \\ \frac{dM_z}{dt} &= -\frac{(M_z - M_o)}{T_1} \end{aligned}$$~~



Spin waves in superfluid ^3He 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

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

Magnon mass

$$m_M \sim \frac{\omega_L}{v_F^2} \sim m_3 \frac{\omega_L}{E_F} \quad (\hbar = 1; \quad c \sim v_F)$$

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

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

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

G.Volovik

Gross-Pitaevskii equation

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

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

Dipole-dipole spin-orbit energy

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

Gradient energy

Spectroscopic energy

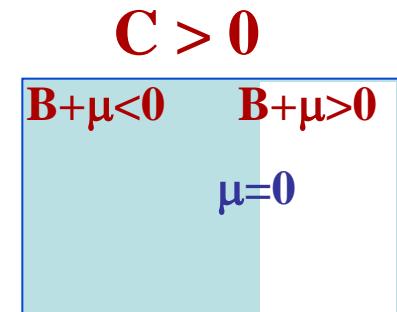
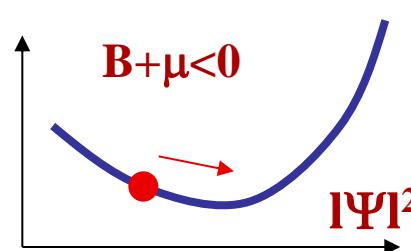
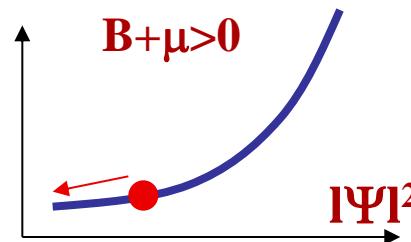
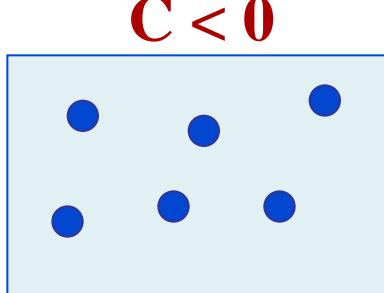
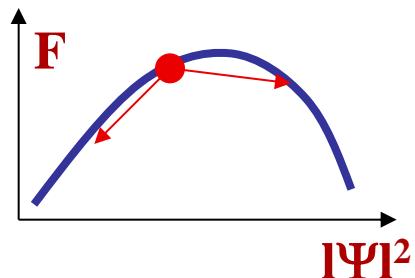
True energy at the rotating frame

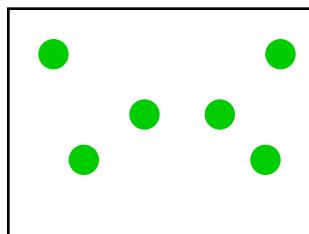
Chemical potential

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

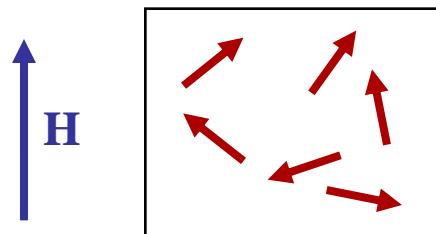
Spin Supercurrent

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



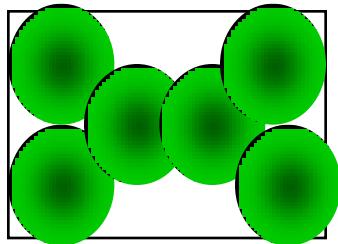


Ideal gas

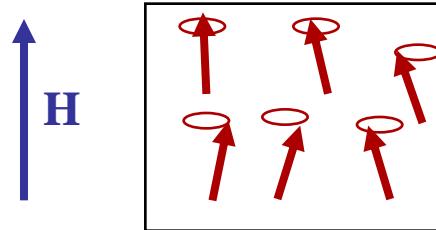


$$\omega = \gamma H_{\text{loc}}$$

Paramagnetic, Fermi liquid

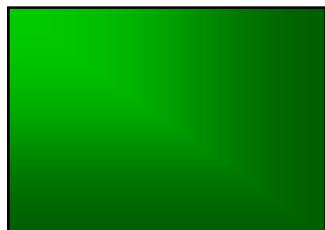


Quantum gas

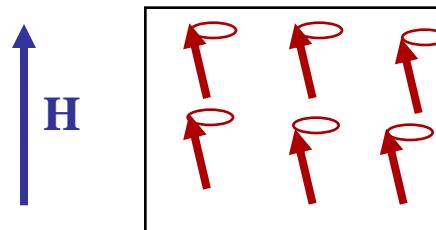


$$i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi + V \psi$$

Magnetically ordered



BEC, superfluidity



$$\omega = \omega_0$$

$$\mathbf{S}_x + i\mathbf{S}_y = \mathbf{S} \sin \beta e^{i\omega t + i\alpha}$$

Coherent precession

Persistent Signal

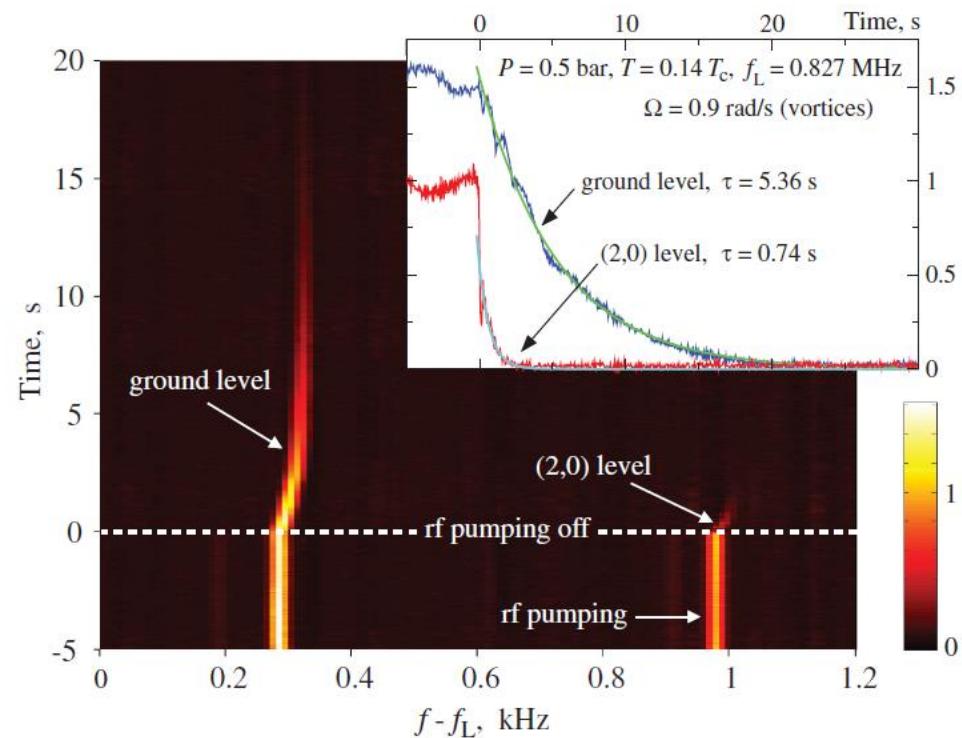
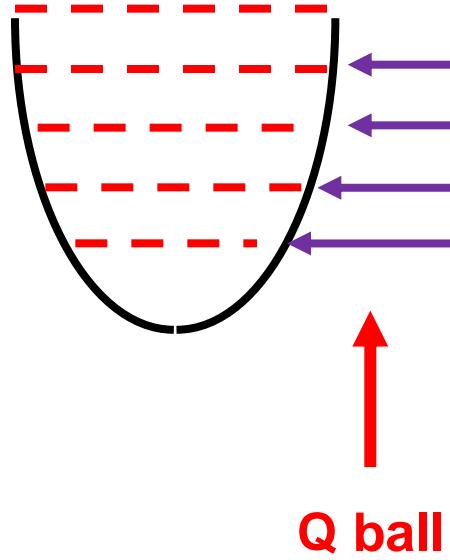
Discovery Yu.M.Bunkov, S.N.Fisher, A.M.Guenault, G.R.Pickett, Phys, Rev, Letters, v.69, p3092, (1992).

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

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

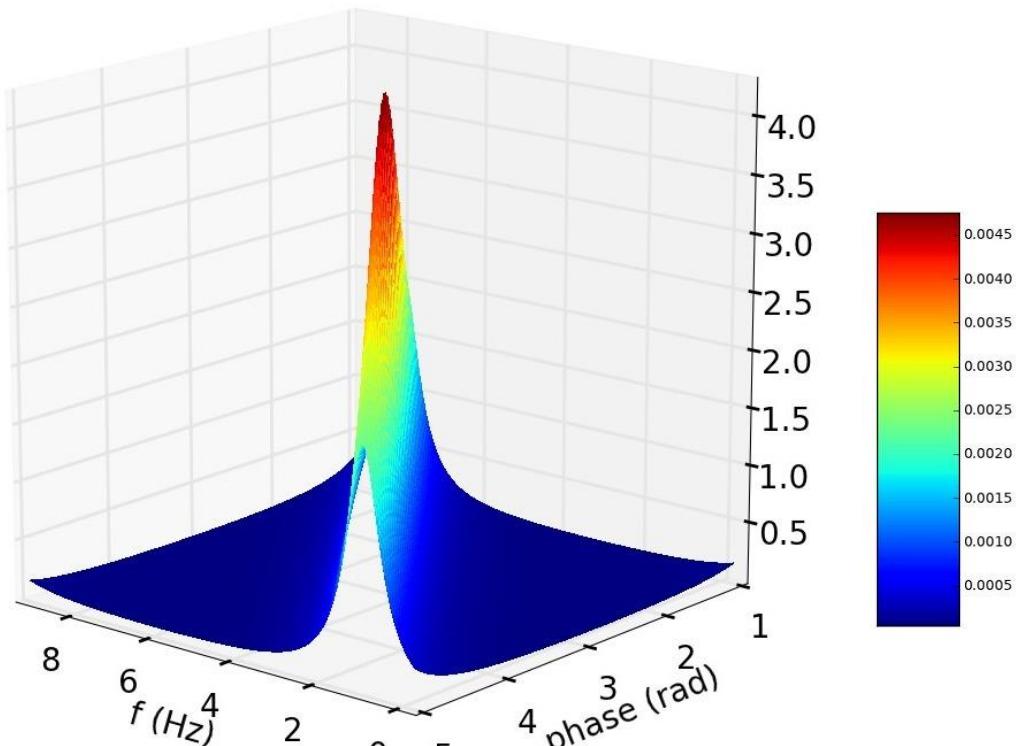
“Magnon Condensation into a Q Ball in $^3\text{He-B}$ ”

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

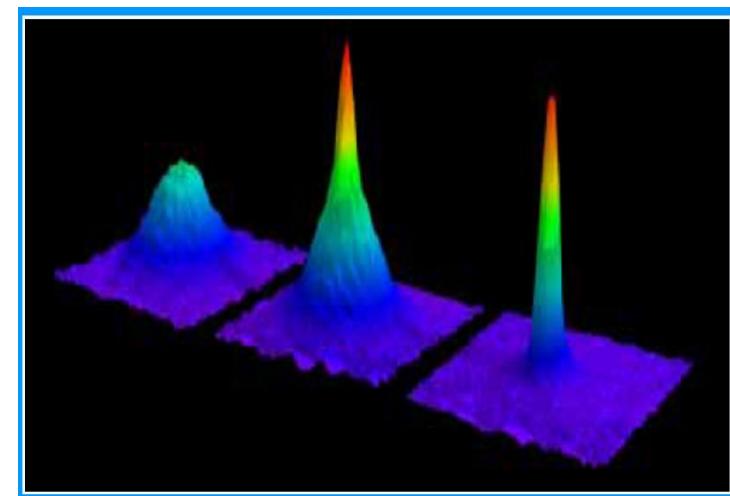


“Self-Ittrapping of magnon Bose-Einstein condensates in the ground and excited levels: from harmonic to a box confinement” S. Autti, Yu. M. Bunkov, V. B. Eltsov, P. J. Heikkinen, J. J. Hosio, P. Hunger, M. Krusius and G. E. Volovik Phys. Rev. Lett. 108, 145303 (2012).

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 condensed! For an atomic BEC the 30% condensation was only achieved!



Magnon BEC



Atomic BEC

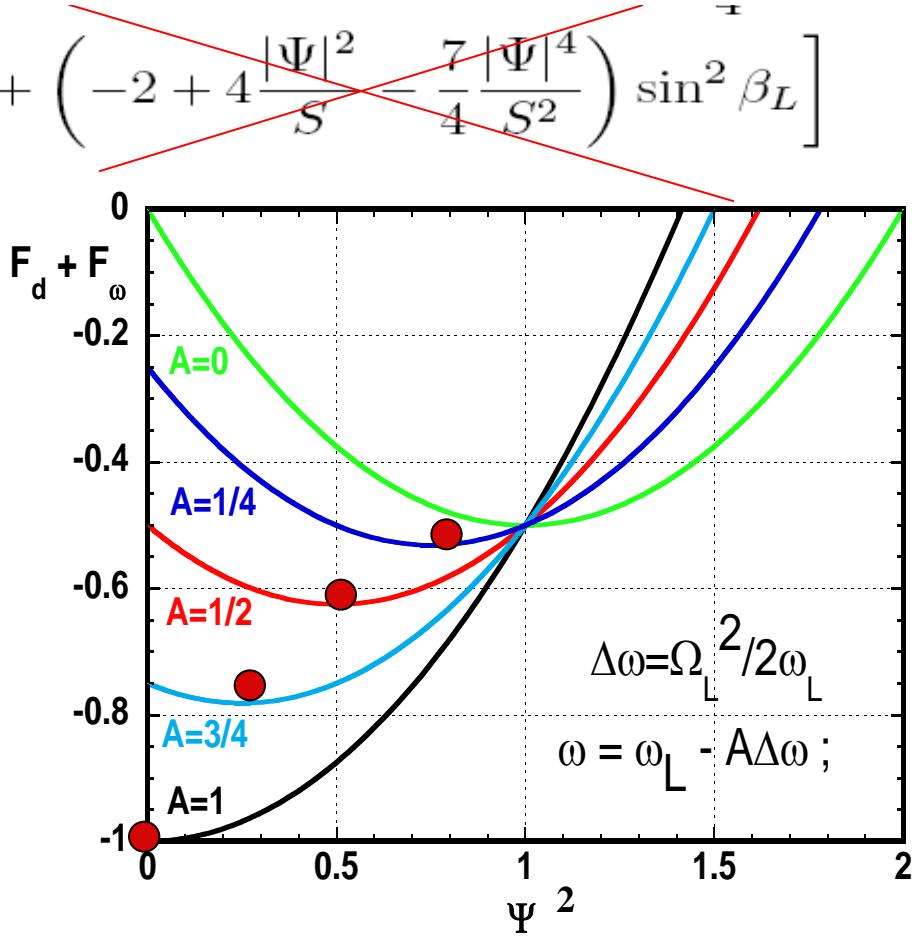
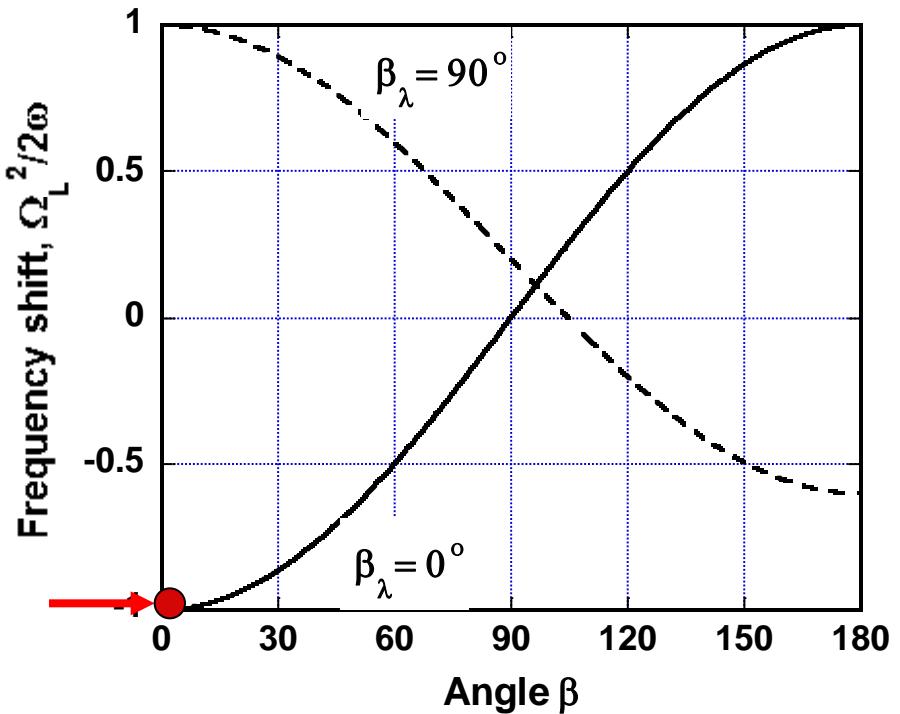
Superfluid $^3\text{He}-\text{A}$ in squeezed aerogel

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

Gross-Pitaevskii equation

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

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



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

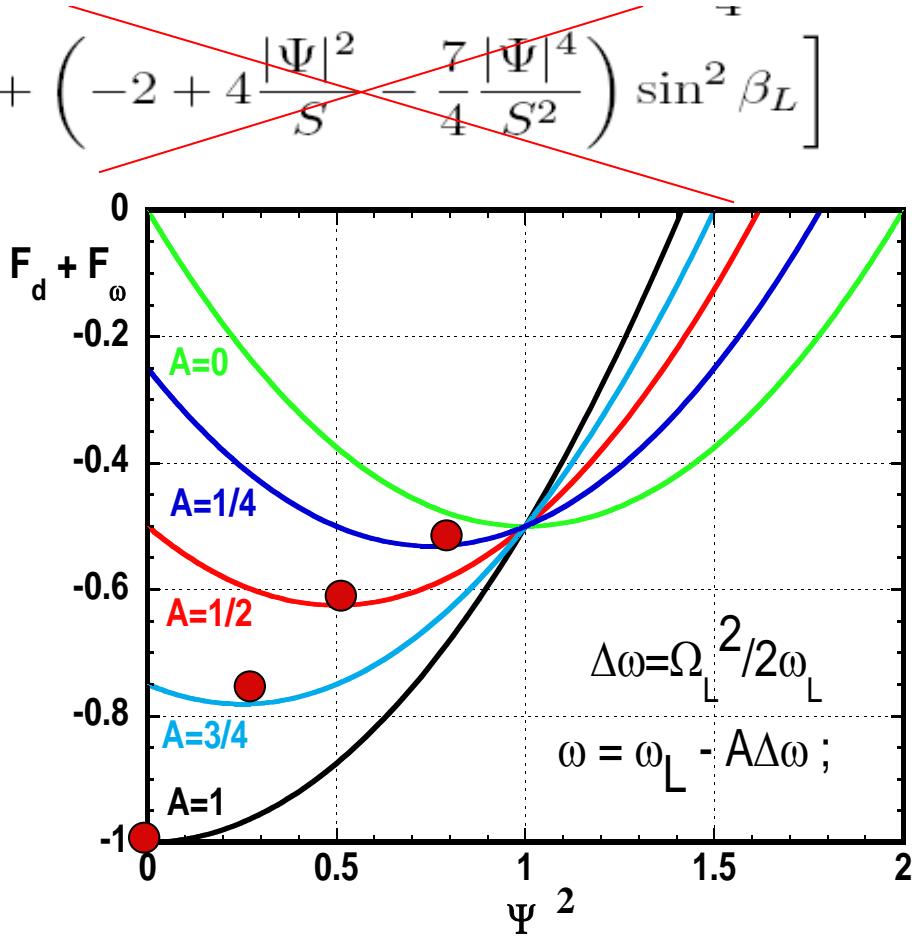
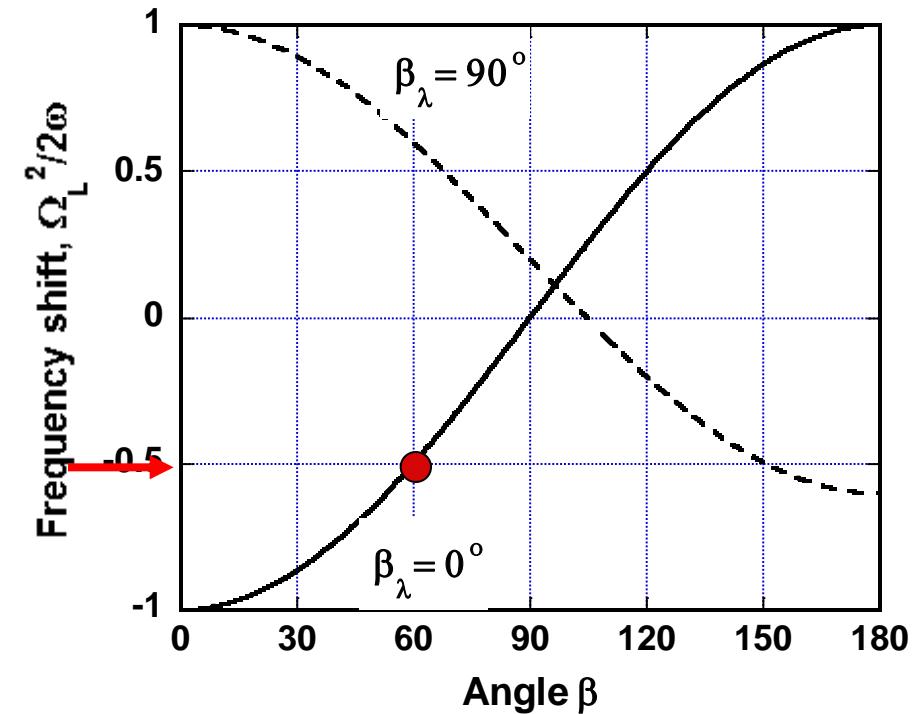
Superfluid $^3\text{He}-\text{A}$ in squeezed aerogel

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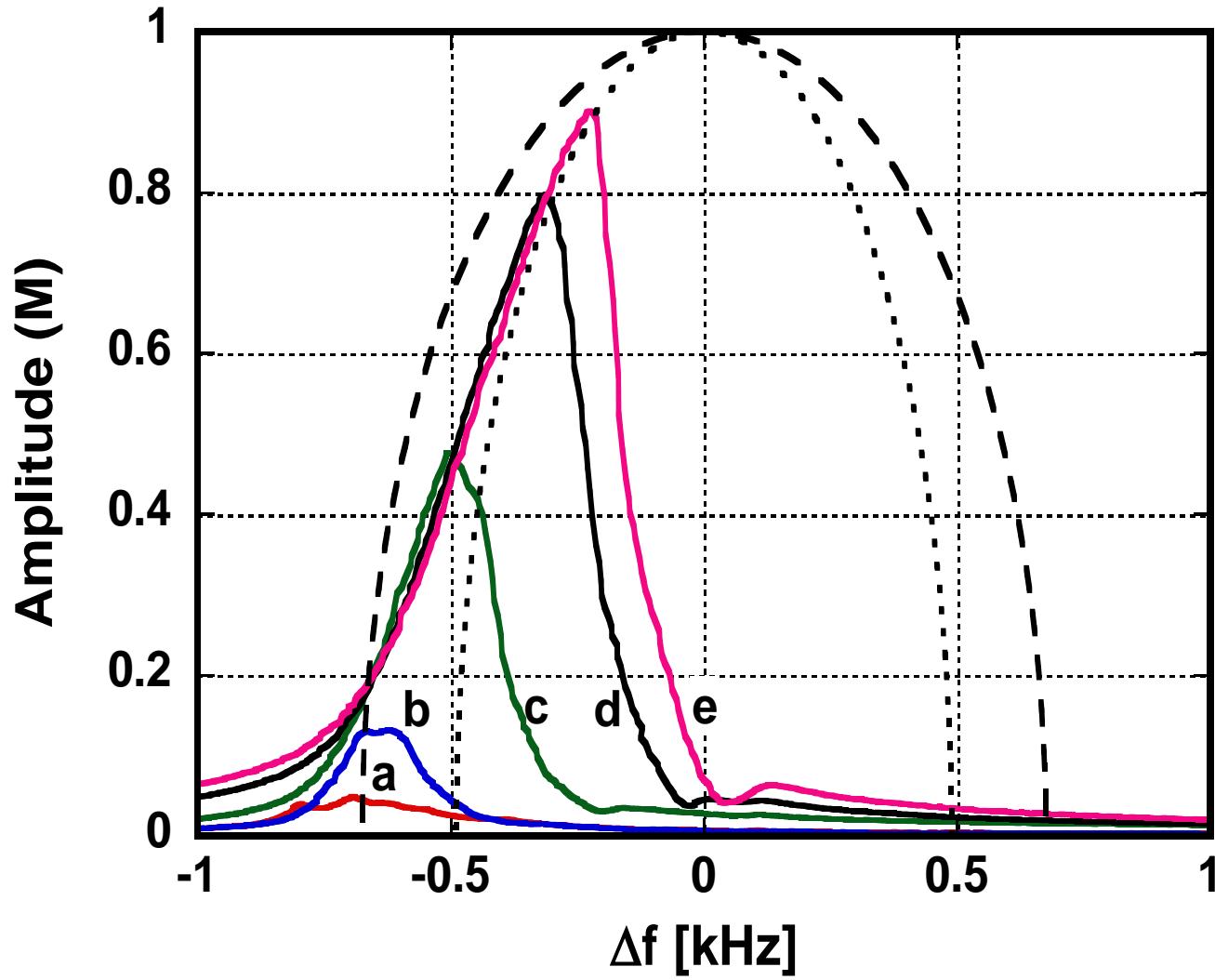
Gross-Pitaevskii equation

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

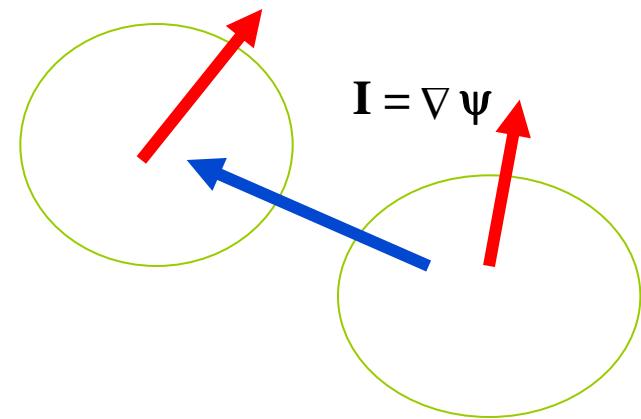
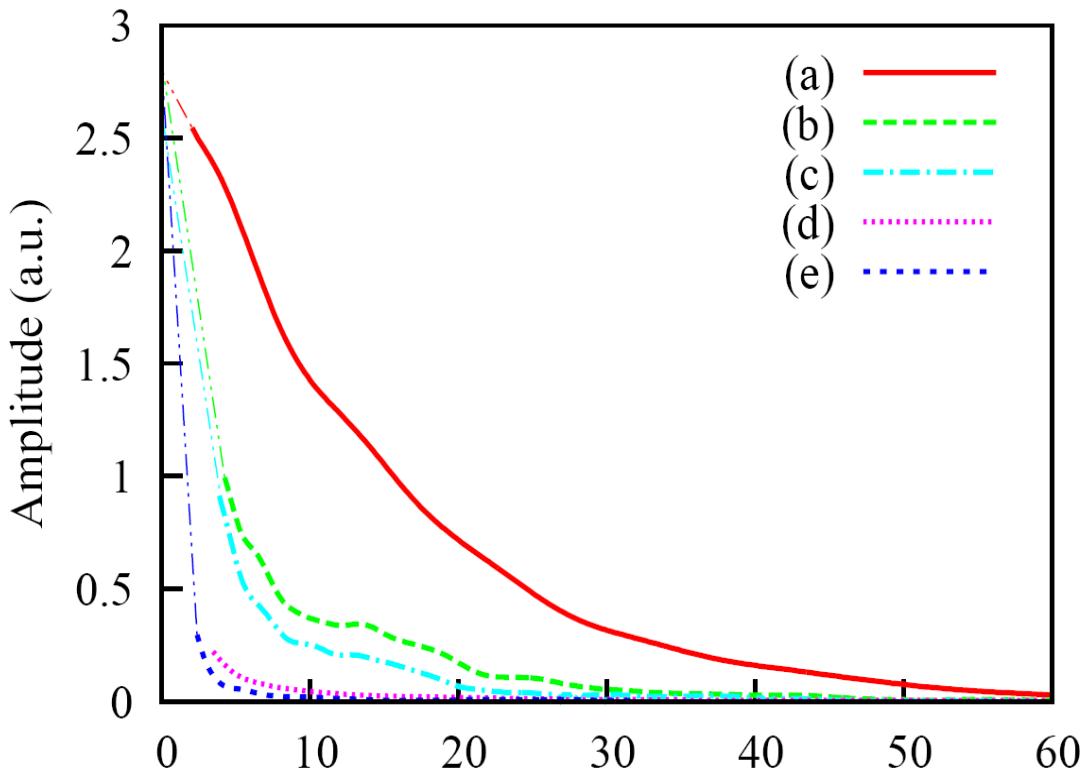
$$F_D = \frac{\chi \Omega_L^2}{4} \left[-2 \frac{|\Psi|^2}{S} + \frac{|\Psi|^4}{S^2} + \left(-2 + 4 \frac{|\Psi|^2}{S} - \frac{7}{4} \frac{|\Psi|^4}{S^2} \right) \sin^2 \beta_L \right]$$



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T. Mizusaki, Yu.M.Bunkov JETP Letters, 86, 244 (2007)



. T. Sato, T. Kunimatsu, K. Izumina, A. Matsubara, M. Kubota, T. Mizusaki, Yu.M. Bunkov
“Coherent Precession of Magnetization in the Superfluid 3He A-Phase”
Phys. Rev. Lett. 101, 055301 (2008)



Curve (a) Free induction decay in superfluid $^3\text{He-A}$ after switching off the RF pumping; 75° .

Curve (b) show the pulsed NMR in the superfluid $^3\text{He-A}$ for deflection angles of 100°

Curve (c) for 70° .

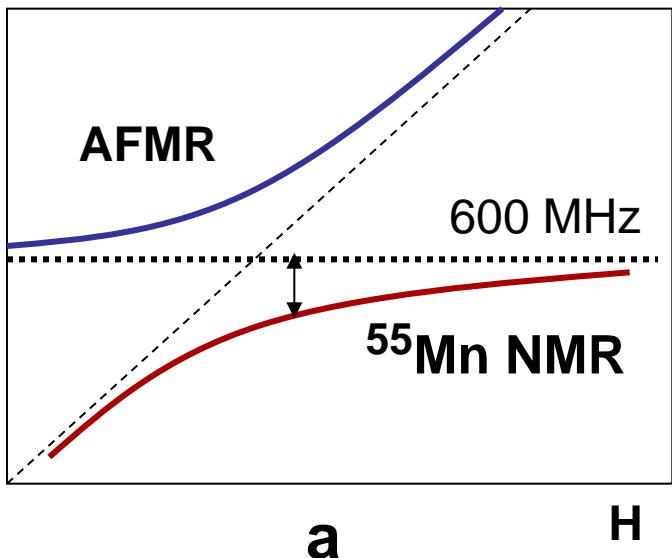
Curve (d) show the free induction decay for “switch-off” and in the normal phase.

Curve (e) show the free induction decay for pulsed NMR

P. Hunger, Y. M. Bunkov, E. Collin, H. Godfrin;
Evidence for Magnon BEC in Superfluid $^3\text{He-A}$

J. of Low Temp. Phys 158, 129–134 (2010)

Coupled Nuclear – Electron precession



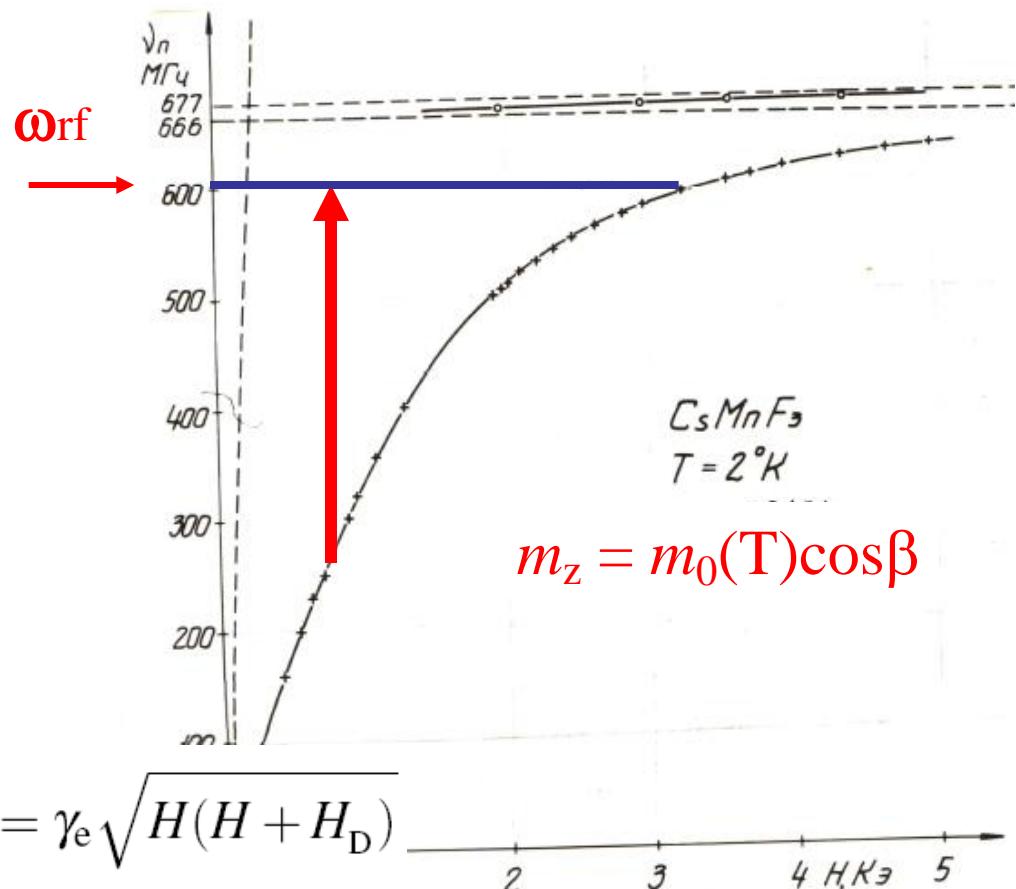
$$\omega^{n0} \omega^{e0} = \omega^n \omega^e$$

$$\omega_k^e = \sqrt{(\omega^{e0})^2 + (\omega_{hf}^e)^2 + k^2 v_s^2}, \quad \omega^{e0} = \gamma_e \sqrt{H(H + H_D)}$$

$$\omega_{hf}^e = \gamma_e \sqrt{2H_E H_{hf}^e}, \quad H_{hf}^e = A \gamma_e m_z,$$

$$\omega_k^n = \omega^{n0} - \frac{\omega_p}{1 + (kr_0)^2}, \quad \omega^{n0} = \gamma_n (H + H_{hf}^n),$$

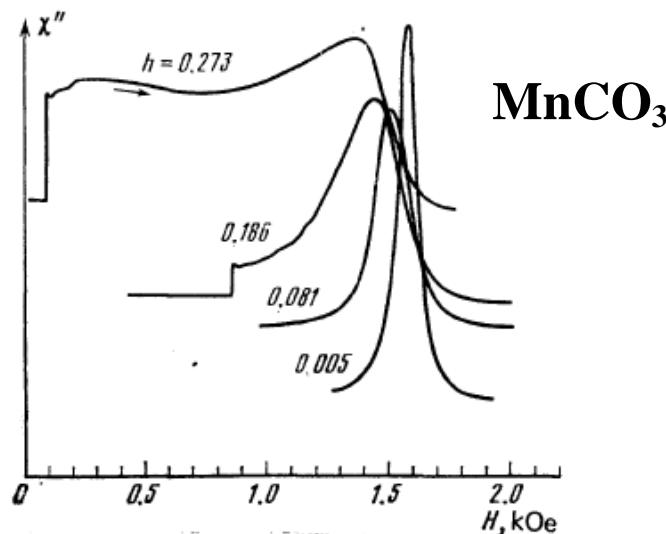
$$\omega_p = \omega^{n0} \frac{H_E H_{hf}^e}{H(H + H_D)} \frac{m_0}{M_0}, \quad H_{hf}^n = A \gamma_n M.$$



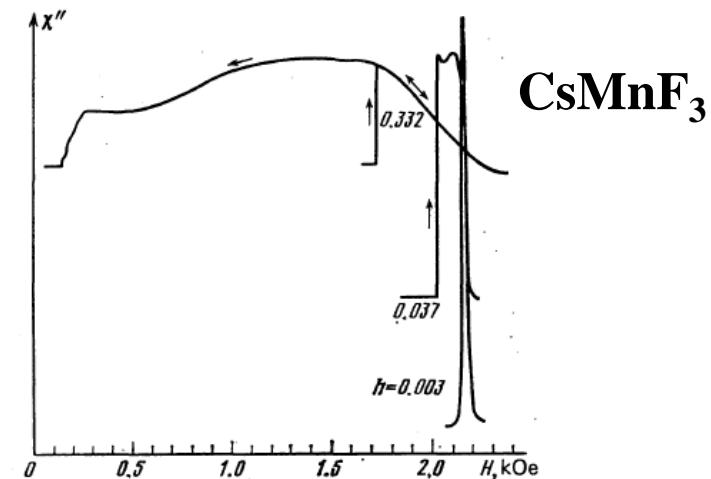
Saturation of nuclear magnetic resonance under conditions of large dynamic frequency shift

V. A. Tulin

Zh. Eksp. Teor. Fiz. 78, 149–156 (January 1980)



MnCO_3



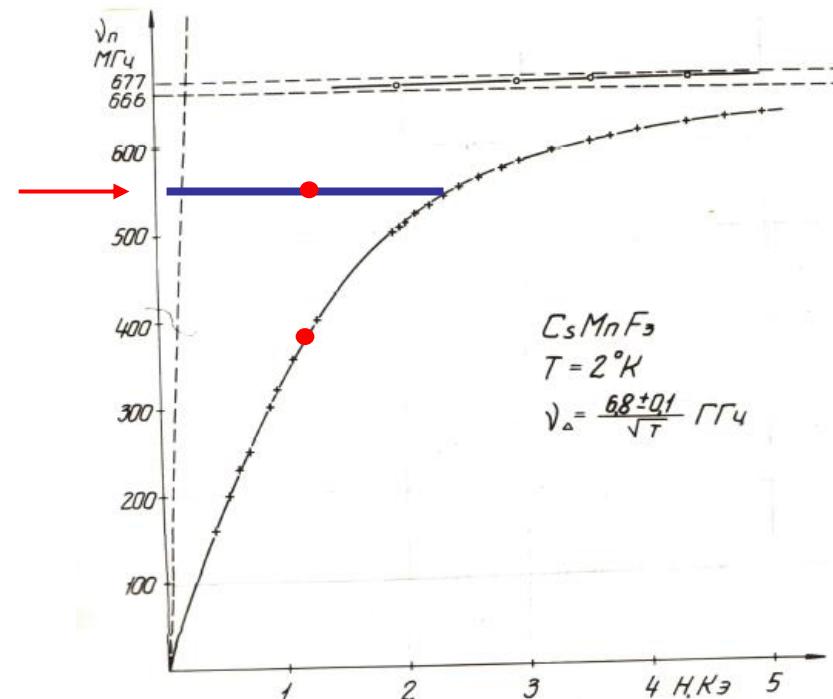
CsMnF_3

M. I. Kurkin calculate the critical energy for lock un state in a therms of Bloch equations.
The shape of the signal was never investigated

$$\frac{dM_x}{dt} = \gamma M_y B_o - \frac{M_x}{T_2}$$

$$\frac{dM_y}{dt} = -\gamma M_x B_o - \frac{M_y}{T_2}$$

$$\frac{dM_z}{dt} = -\frac{(M_z - M_o)}{T_1}$$



$$v_n / M\Gamma_4 = \frac{68 \pm 0.1}{\sqrt{T}} \Gamma\Gamma_4$$

$$\omega_k^e = \sqrt{(\omega^{e0})^2 + (\omega_{hf}^e)^2 + k^2 v_s^2}, \quad \omega^{e0} = \gamma_e \sqrt{H(H + H_D)}, \quad \textcolor{red}{\sim 500 \text{ mT}}$$

$$\omega_{hf}^e = \gamma_e \sqrt{2H_E H_{hf}^e}, \quad H_{hf}^e = A \gamma_e m_z, \quad \textcolor{red}{\sim 0.1 \text{ mT}}$$

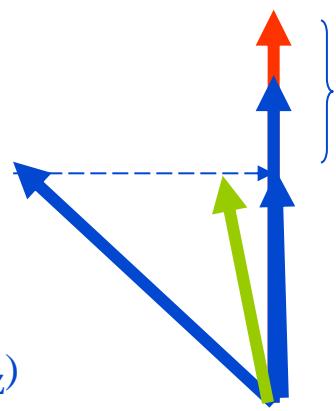
$$\omega_k^n = \omega^{n0} - \frac{\omega_p}{1 + (kr_0)^2}, \quad \omega^{n0} = \gamma_n (H + H_{hf}^n), \quad \textcolor{red}{\sim 100 \text{ T}}$$

$$\omega_p = \omega^{n0} \frac{H_E H_{hf}^e}{H(H + H_D)} \frac{m_0}{M_0}, \quad H_{hf}^n = A \gamma_n M.$$

Paramagnetic system

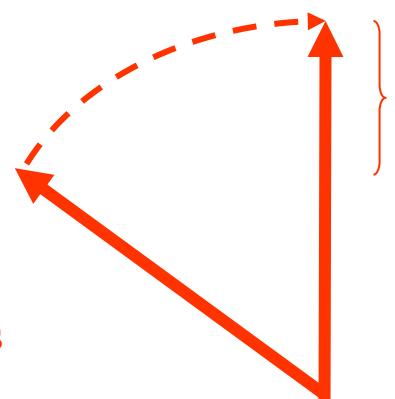
$$\mathbf{S} = \chi(T) \mathbf{H}$$

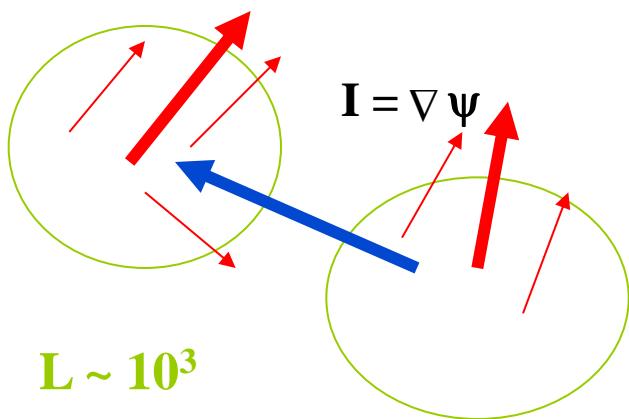
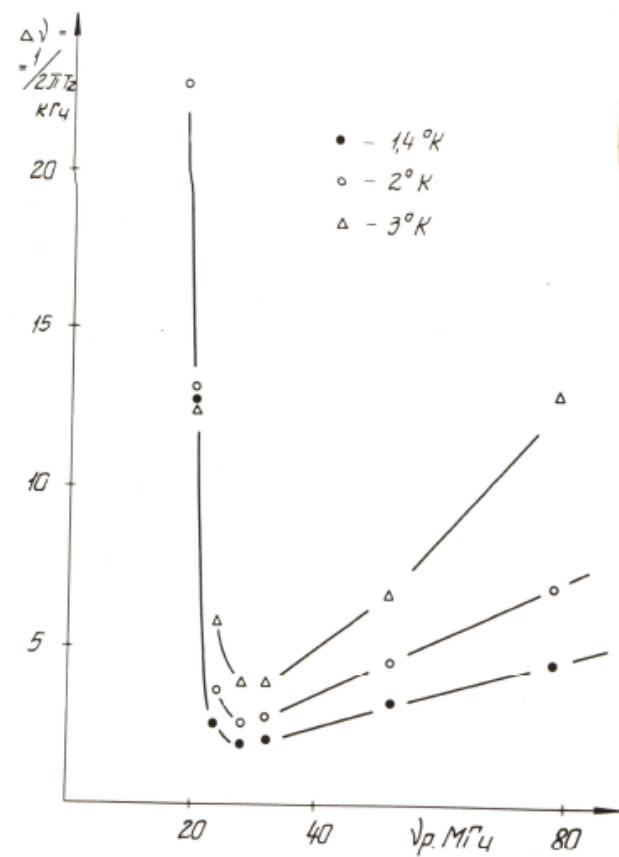
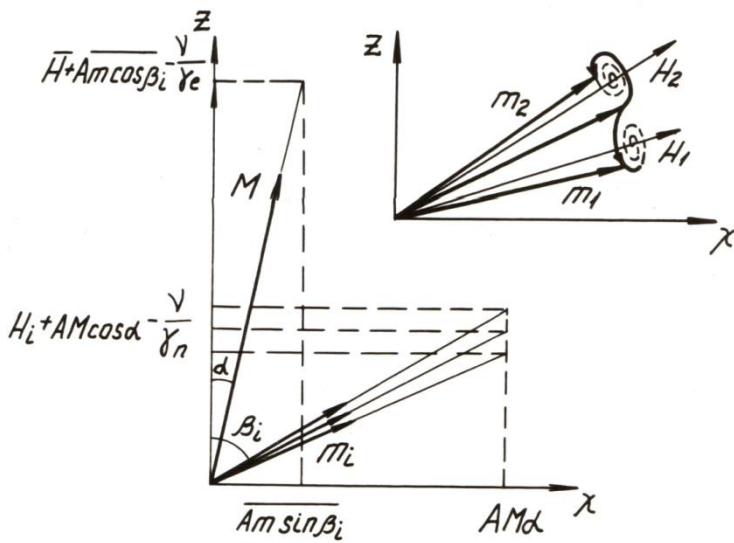
Thermal excitations $(\mathbf{S}_{z0} - \mathbf{S}_z)$



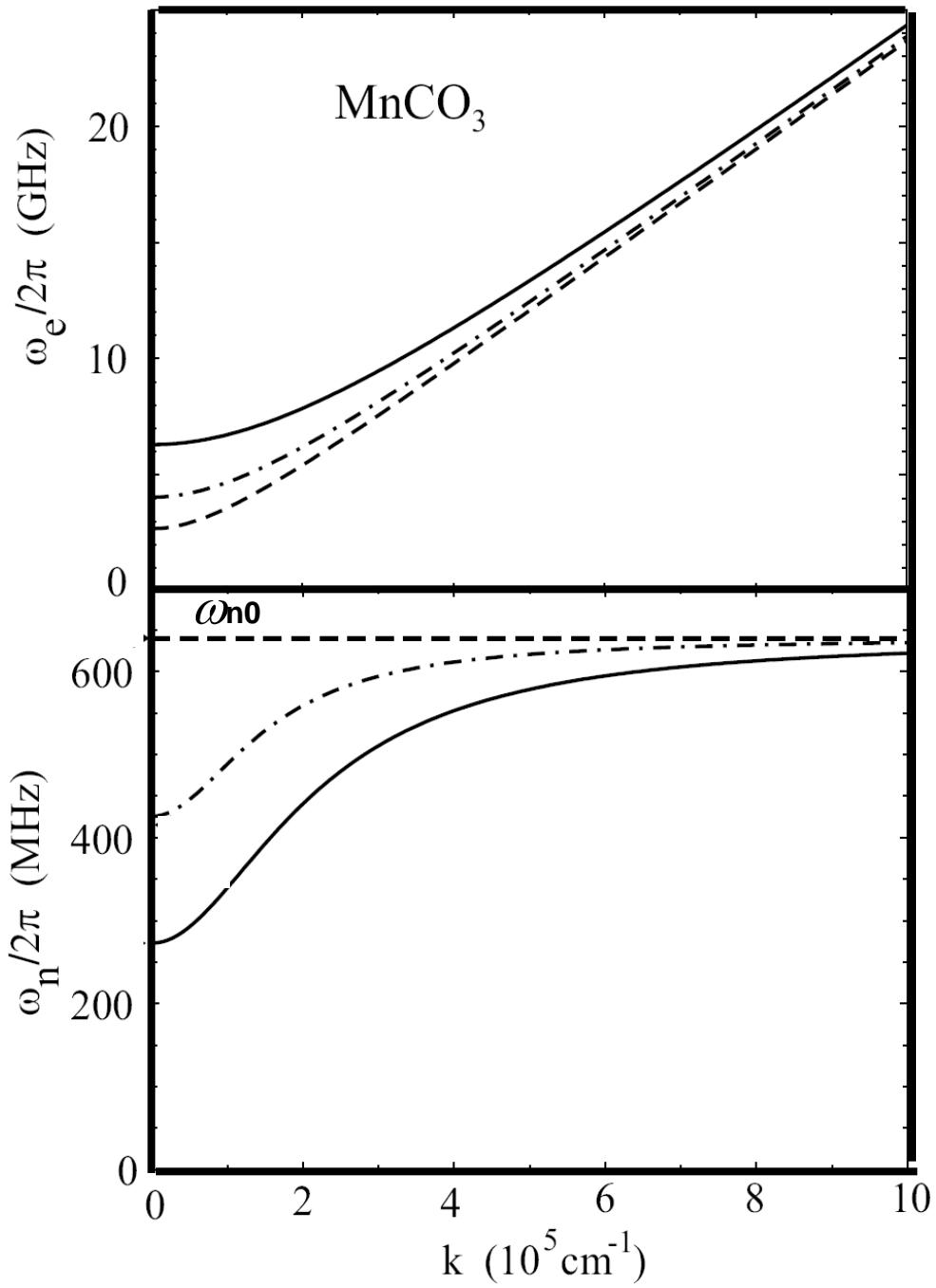
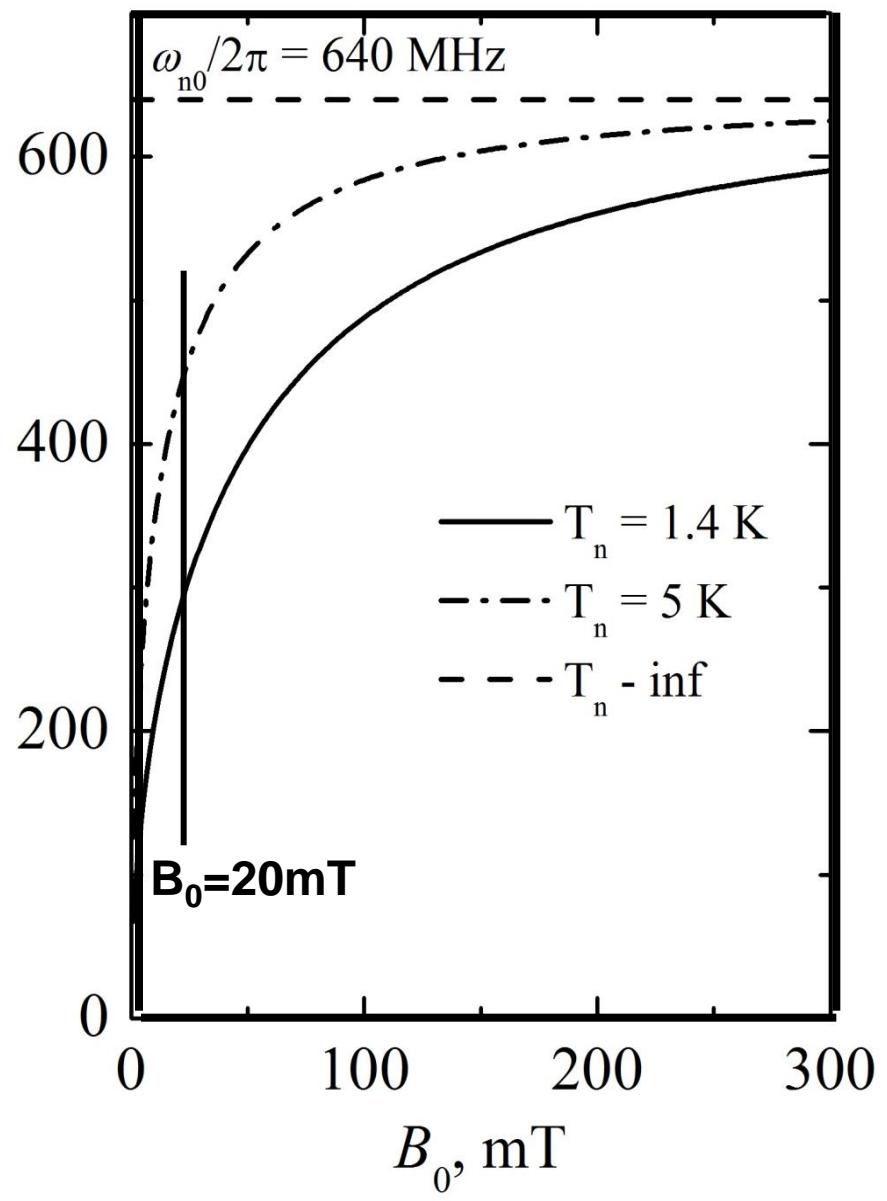
Superfluid ${}^3\text{He}$
Antiferro with big pulling

Locally coherent magnons

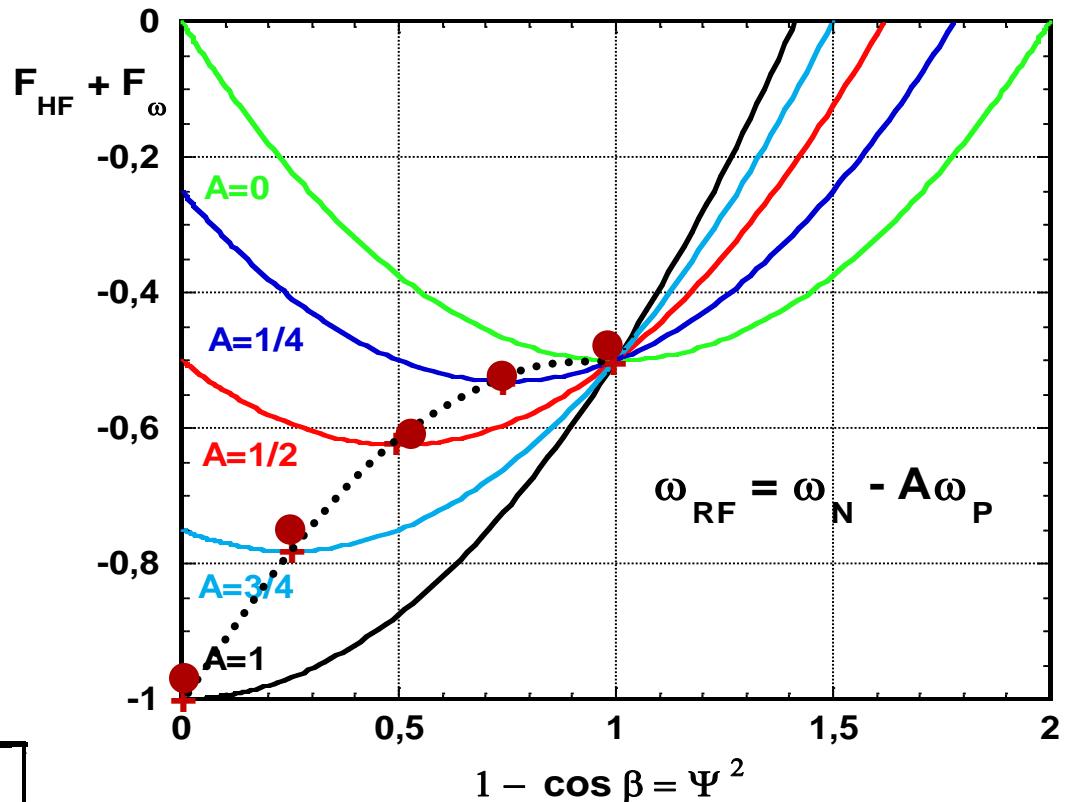
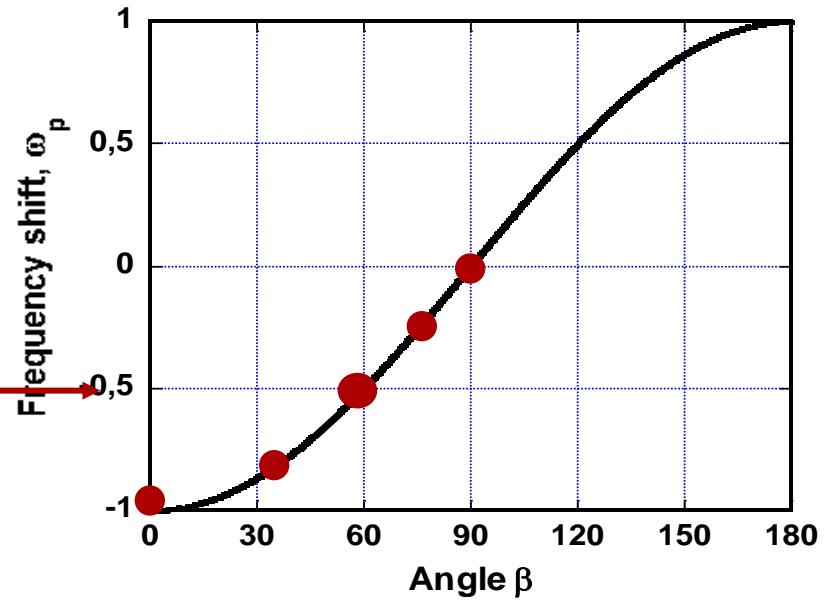


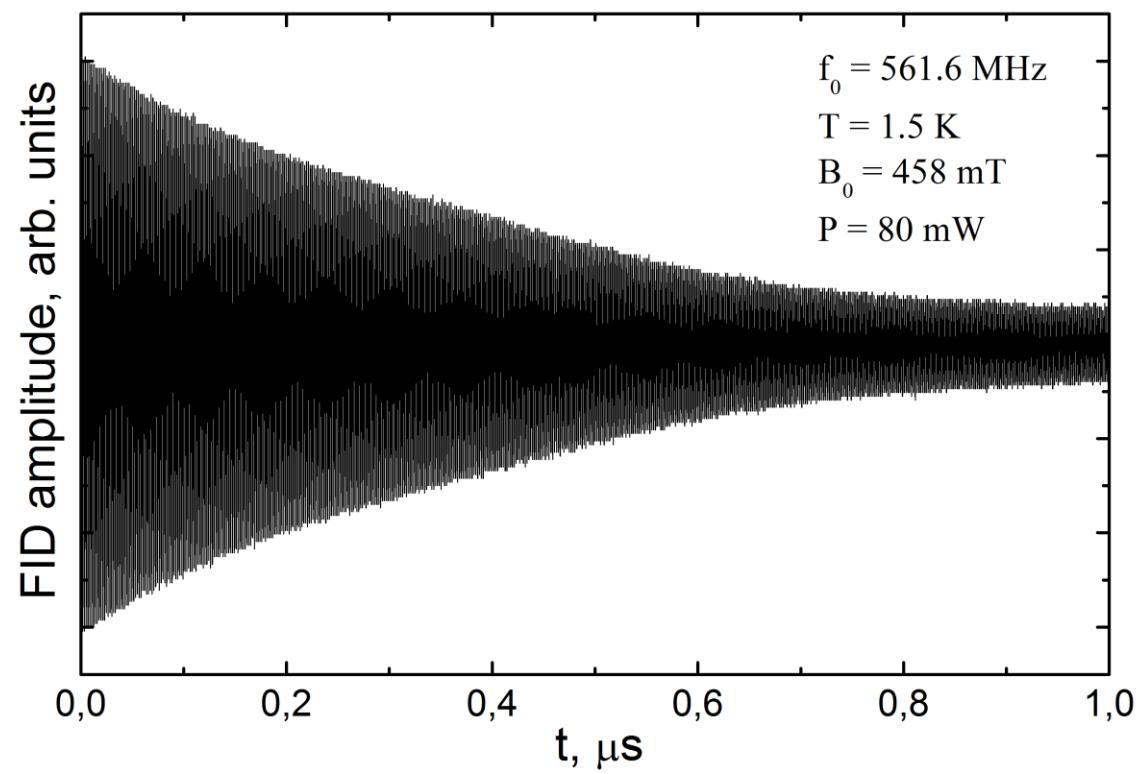
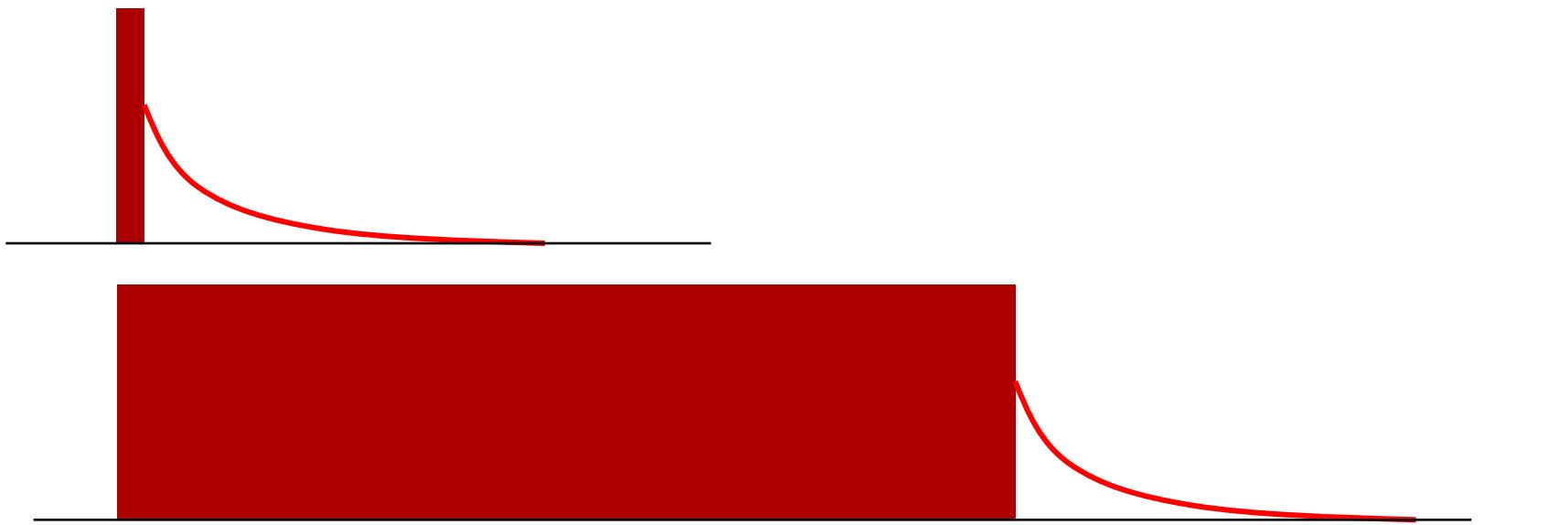


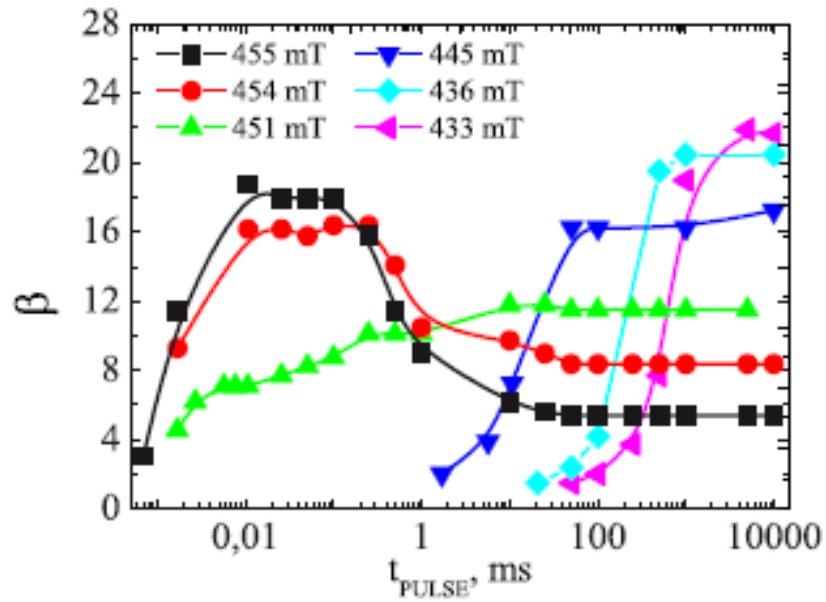
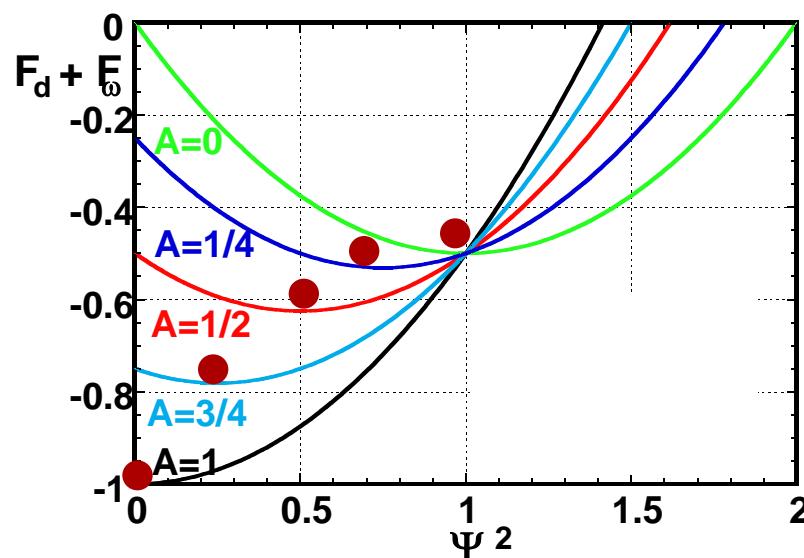
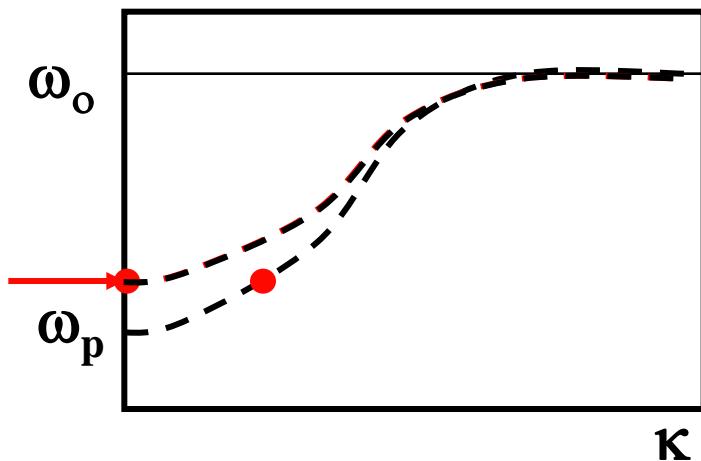
Yu. M. Bunkov Diploma
Master degree Kapitza institut 1974



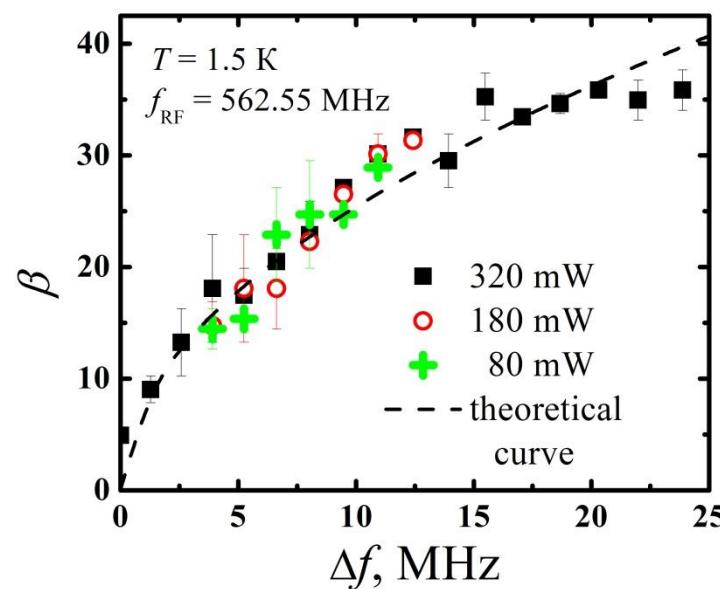
$$\omega^n = \omega^{n0} - \omega_{p0} \cos \beta$$





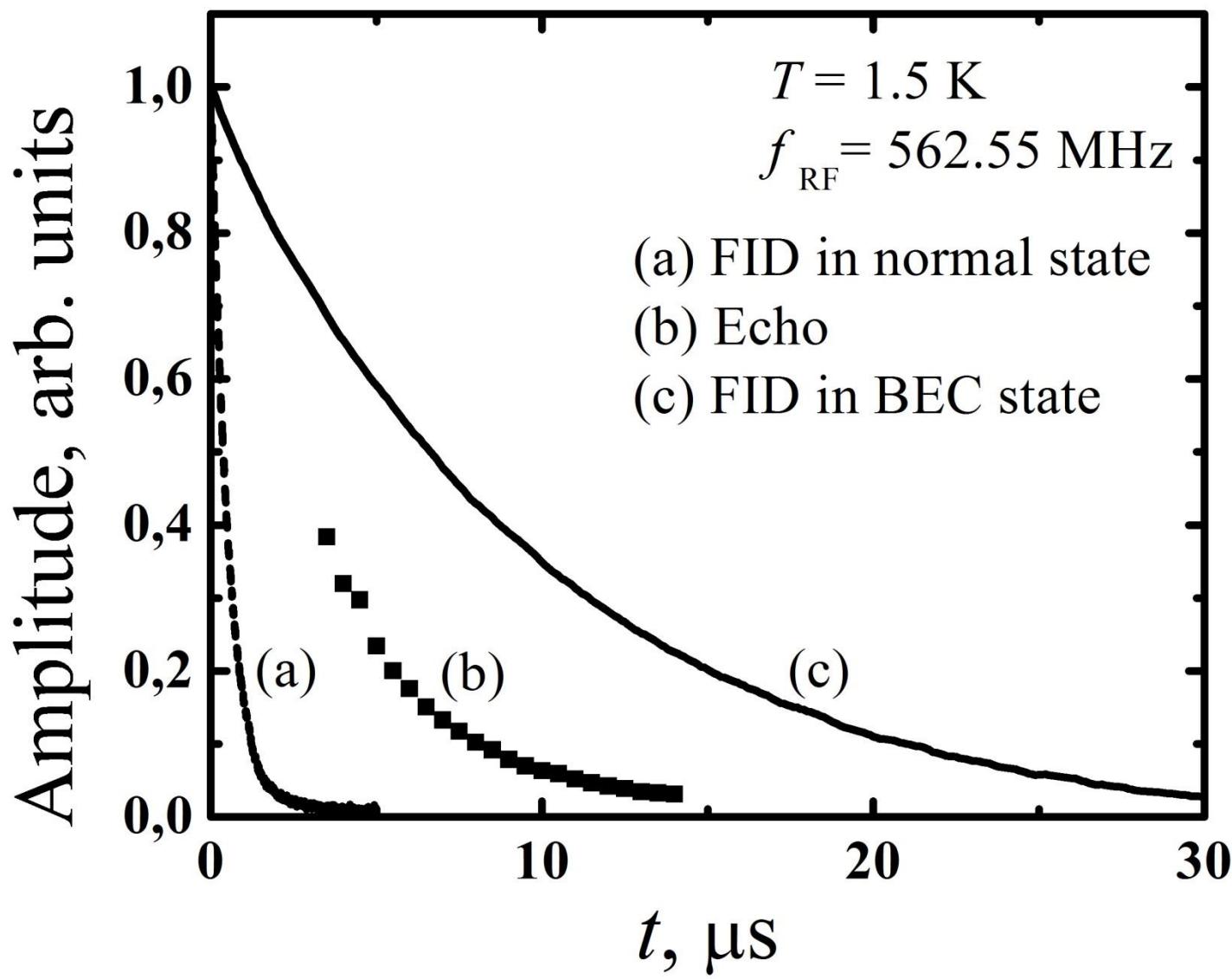


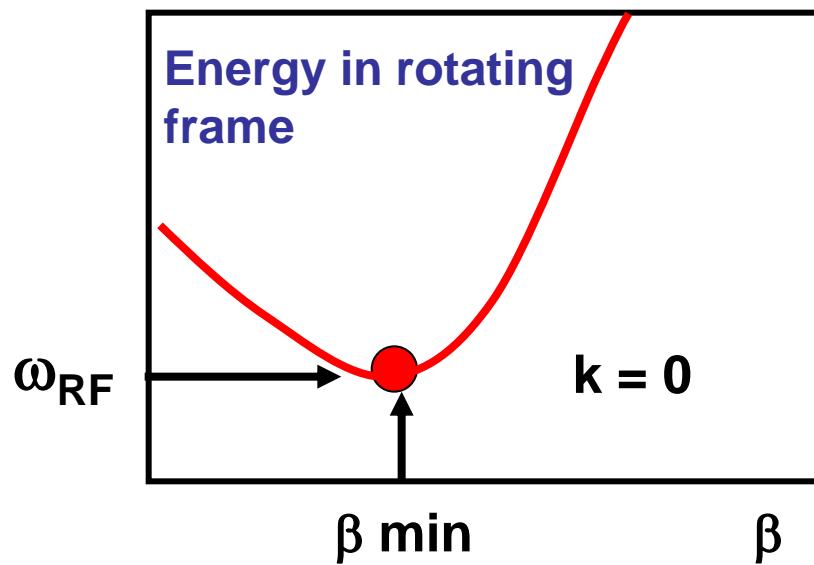
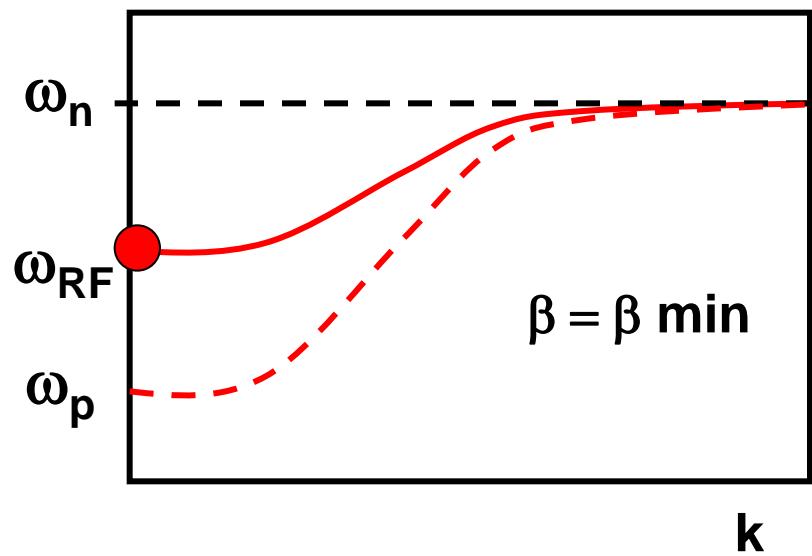
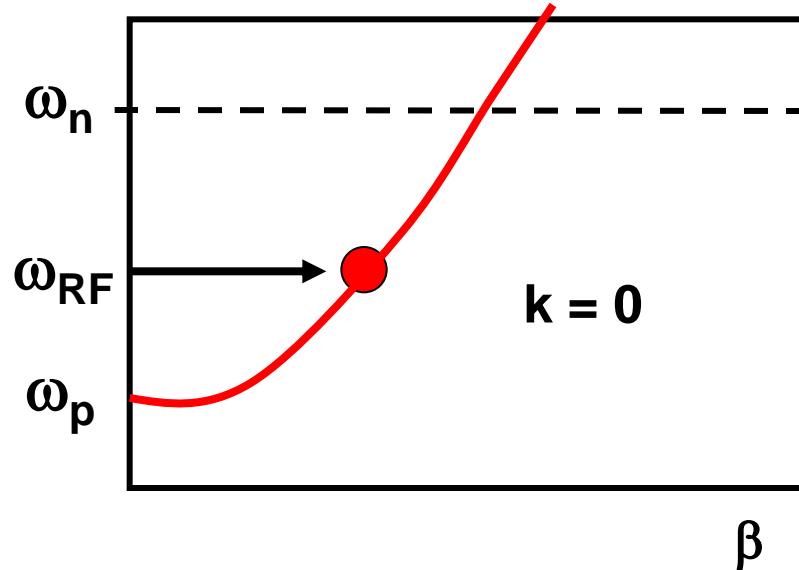
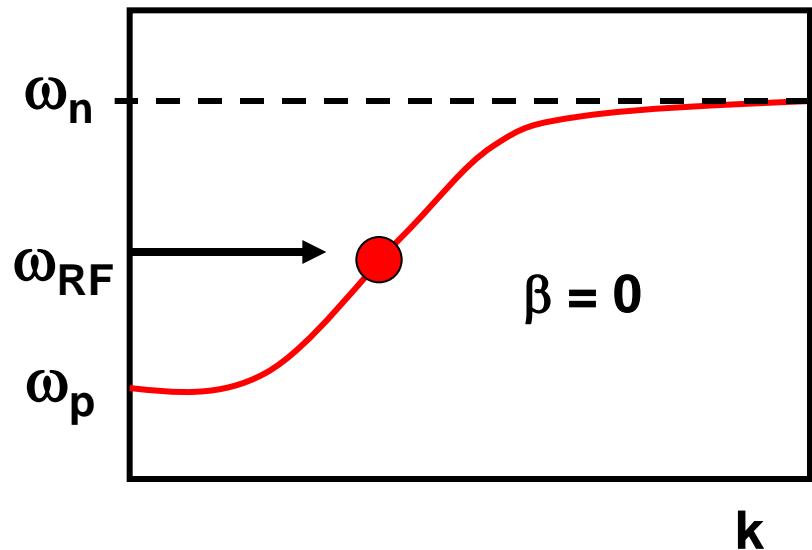
FID amplitude vs. RF pulse length
at different magnetic fields



Signal intensity vs. frequency shift

Yu. M. Bunkov, E. M. Alakshin, R. R. Gazizulin, A.V. Klochkov, V.V. Kuzmin,
V.S. L'vov, and M.S. Tagirov. "High T_c spin superfluidity in antiferromagnets",
Phys. Rev. Lett. 108, 177002 (2012).





Noise Pumping of Nuclear Spin Waves in an Antiferromagnet

A. V. Andrienko

Journal of Experimental and Theoretical Physics, Vol. 100, No. 1, 2005, pp. 77–88.

BEC of magnons at the parametric excitation

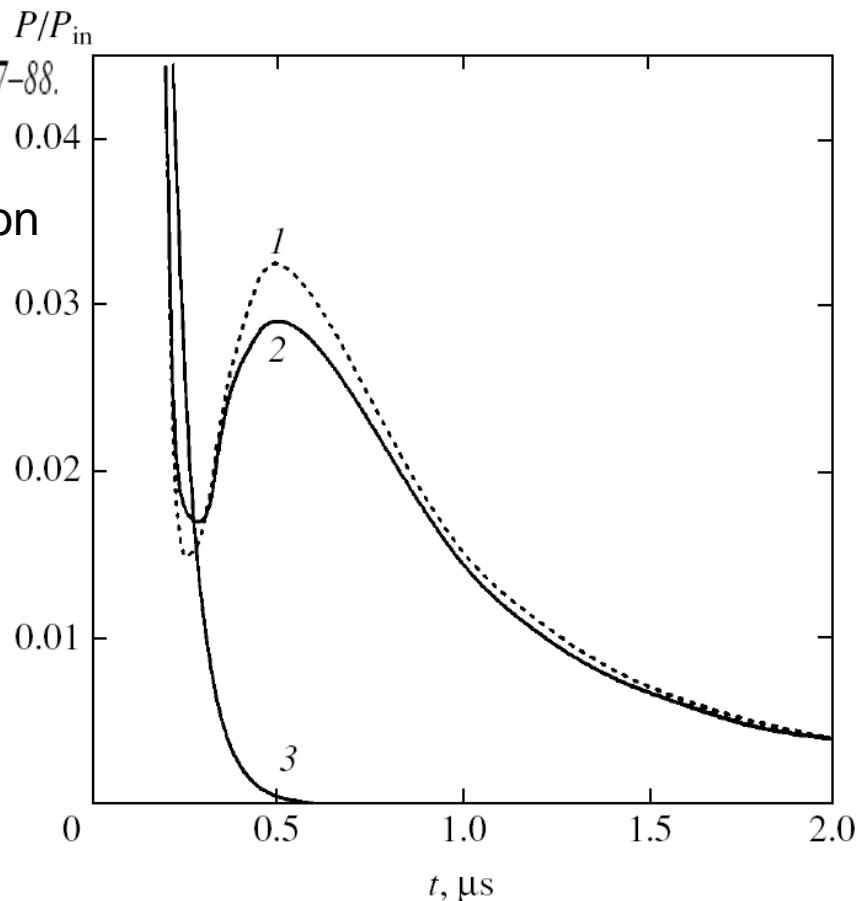
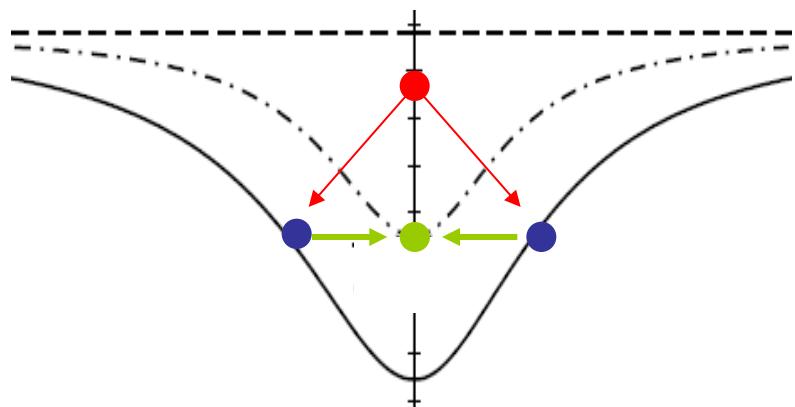


Fig. 10. Oscillograms of the trailing edge of microwave pulses and a signal of electromagnetic radiation from a sample for $T = 2.08$ K, $H = 1790$ Oe, $P_{\text{in}} \approx 2000P_c$, and $\omega_p = \omega_R - 2\pi \times 0.7$ MHz for (1) monochromatic pumping and (2) noise pumping. Curve (3) represents the trailing edge of a pulse for $P < P_c$; $t = 0$ corresponds to the moment of switching off the pump oscillator.

Conclusions

The spin systems with strong Suhl – Nakamura interaction has many similarities with superfluid ^3He and particularly with $^3\text{He-A}$ in squeezed aerogel

The long lived induction decay was found after a magnon BEC condensation under a strong RF field. The signal is longer then the T_2 after a short pulses

The coherence of the induction signal manifest the existence of coherent spin current which prevent the dephasing.

The new CW NMR data shows the frequency dependence of the signal more complicate then it was in CsMnF_3 previous publications. It may be related with week ferromagnetism of MnCO_3 , relatively small frequency shift, different orientation of RF field versus easy plain and magnetic field a complicate involvement of electron spin subsystem. See poster.

$$M_{+}^z \approx -4 \frac{M_0}{H_0} H_1 \cos \omega t + \frac{\gamma^2 H_E H_n}{\omega_+^2} m_{+}^z,$$

$$M_{+}^y \approx \frac{H_n}{H_E} m_{+}^y,$$