To Dubna-2007 Workshop

On behalf of the COMPASS collaboration

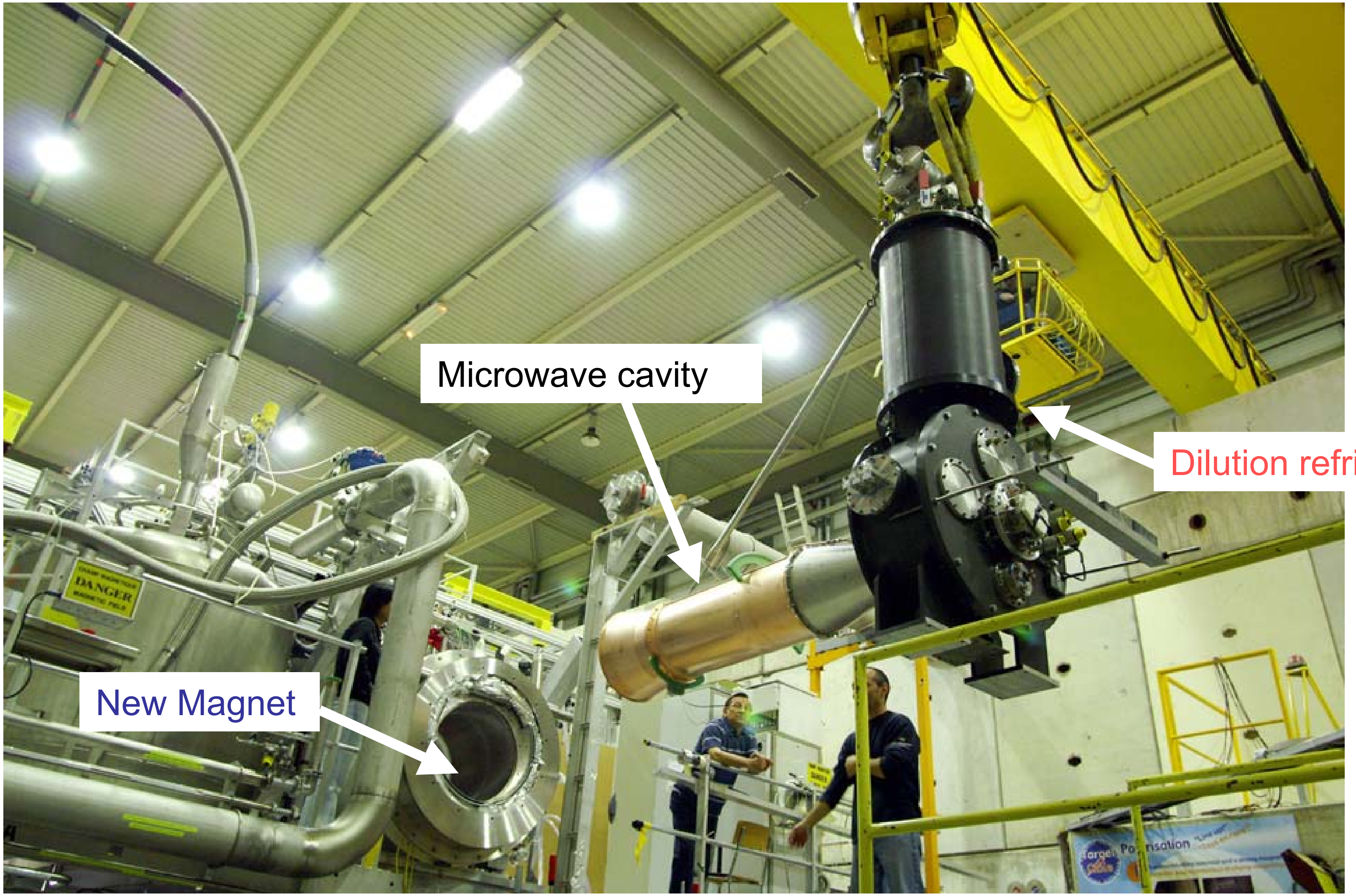
Yu. Kiselev and W. Meyer

Nonlinear Magnetic Phenomena in Highly Polarized Target Materials

We briefly summarize and survey nonlinear magnetic phenomena observed at high nuclear polarizations

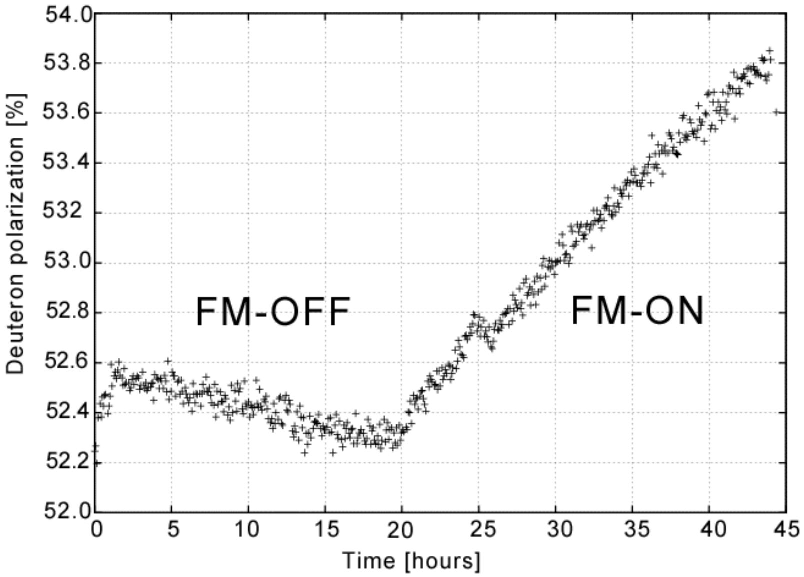
1. **Frequency modulation effect**
2. **Distortions of the NMR line shape**
3. **Polarization by cross relaxation between nuclear species in NH3**
4. **Maser and superradiation phenomena**
5. **Detection of the electromagnetic radiation emitted by negatively polarized nuclei at low magnetic fields**

COMPASS polarized target mounting



Frequency modulation effect

In a target polarized by the Dynamic Nuclear Polarization (DNP) method the frequency modulation effect enables record polarizations as the result of the multimode irradiation of the target material at about 0.1 K temperatures.



The plot shows the build-up of deuteron polarization in LiD over time with and without FM

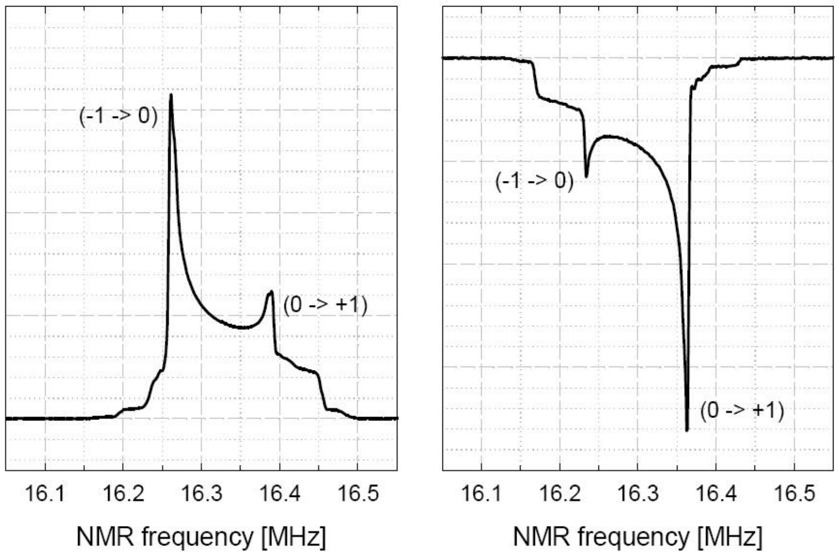
See about FM: →

Y.F. Kisselev, Nucl. Instr. And Meth., A 356, 99 (1995);

Y. F. Kisselev et. al., Proceeding of the 11_th Int. Workshop on Polar. Sources and Target, Tokyo. Japan, 14 -17 Nov. 2005, p.63.

Distortions of the NMR line shape

The high nuclear polarization causes the strong asymmetry of the NMR line shape of deuterons.

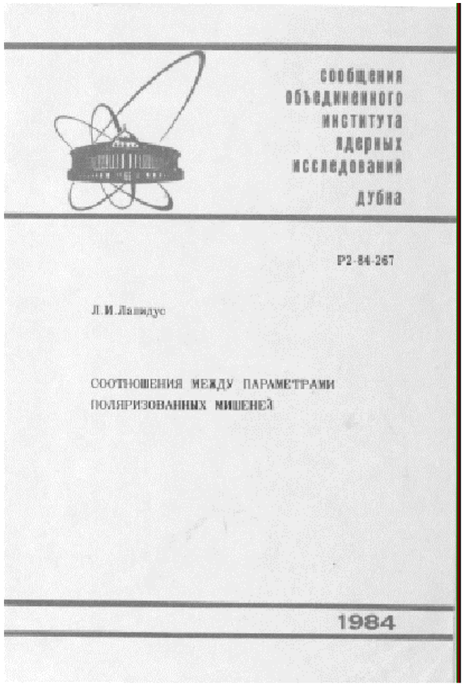


NMR-signals of D-propanediol (left) and D-butanol (right) with record polarizations of -81 % and +80 %, respectively

(Bochum, Germany, S.T. Goertz et al., NIM A 526 (2004) 43-52).

Our Workshop is devoted to the blessed memory of Prof. L.I. Lapidus.

The important formulas for the calculation of the polarization and alignment were obtained in his last publication.



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Л.И.Лапидус

СООТНОШЕНИЯ МЕЖДУ ПАРАМЕТРАМИ
ПОЛЯРИЗОВАННЫХ МИШЕНЕЙ

1984

Well known that, in the case of a week quadrupole interaction, the nuclear polarization for S=1 is calculated by the formula

$$P_1 = \frac{4\tanh^2\frac{x}{2}}{3+\tanh^2\frac{x}{2}} ,$$

where x is the ratio of Zeeman to Boltzmann energy.

The general formula for the nonzero quadrupole interaction was obtained by L. I. Lapidus in Dubna (1984) :

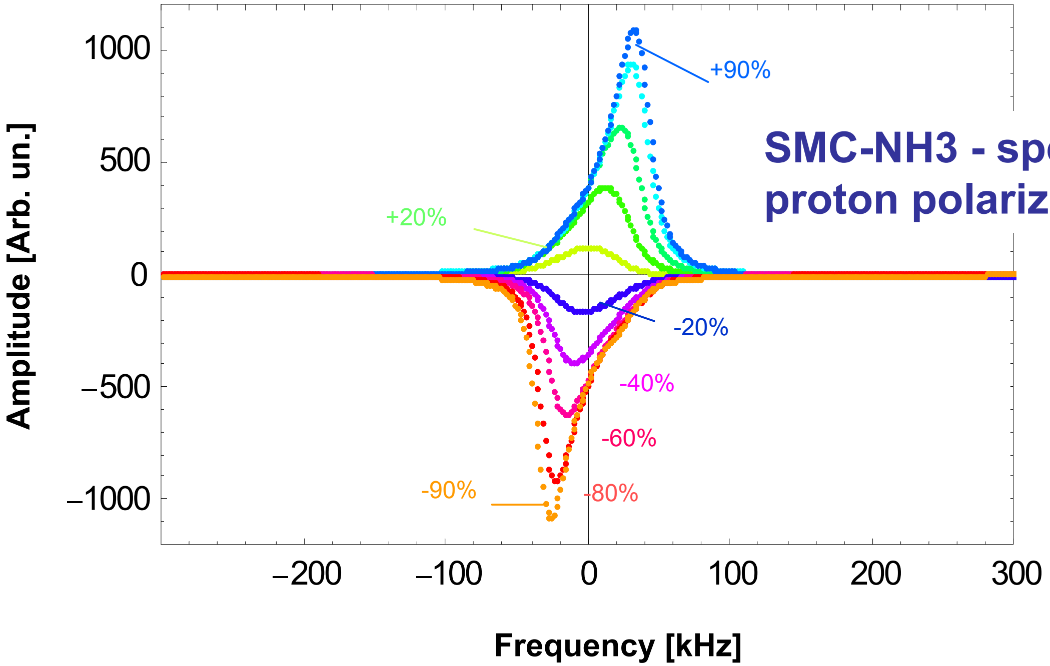
$$P_N = P_1\left[1 - \frac{(1-\tanh^2\frac{x}{2})(1-e^{-y})}{1+2e^{-y}+(2e^{-y}-1)\tanh^2\frac{x}{2}}\right] .$$

here y describes a quadrupole interaction. He has shown that at the nonzero ($y\neq 0$) quadrupole interaction the nuclear signal should have an asymmetrical lineshape even at zero polarization.

For the fist time, I verified Lapidus's formula for N_{14} –nuclei asymmetry in NH_3. It gives 1.46 correction factor at zero polarization which is in an excellent agreement with our data (Yu.F. Kisselev, SMC-note, SMC/96/9, CERN/PPE).

Distortions of the NMR line shape

A strong signal asymmetry was also seen for the case of dipole-dipole interaction between the three protons in the NH3 target material



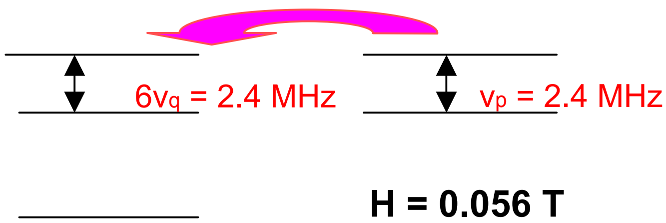
SMC-NH3 - spectra at different proton polarizations.

(B. Adeva et al., NIM in Phys. Res. A 419 (1998) 60-82)

Our studies show that the signal asymmetry is proportional to the proton polarization. This allows to determine the proton polarization by the line shape of NMR-spectra.

Polarization by cross relaxation between nuclear species in NH3

The method was tested by SMC collaboration at CERN . It can be applied for the fast polarization of radioactive nuclei implanted in a highly polarized proton target. In method, the high proton polarization is quickly transformed to the lower polarized spins by means of cross relaxation, for example:



N_{14}-spins in NH3 reach only 14% during usual DNP-polarization at 2.5 T and 0.1 K. But in 0.056 T field Zeeman proton and N14 quadrupole energy splitting are equalized and for some millisecond interval polarized protons enlarged N_{14} polarization up to 50 % .

See about CR:

B. Adeva, Ch. Dulya, J. Kyynäräinen et al., CERN Preprint, Geneva, 16 June 1997, CERN-PPE/97-66.

F.S. Dzheparov and Yu.F. Kisselev, Pis'ma Zh. Eksp. Teor. Fiz., vol. 68, 539 (1998).

Yu.F. Kiselev and V.L. Lyuboshitz, Phys. of Atom. Nuclei, Vol.64, No. 1, 17-26, 2001

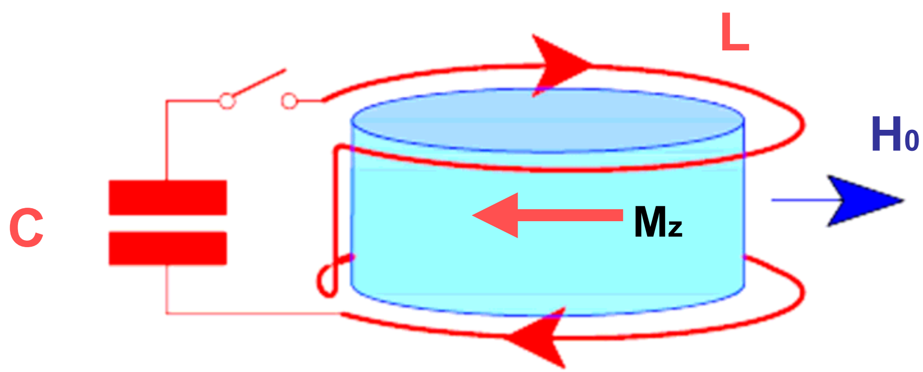
Maser and superradiation phenomena

Used Bloch and Kirchhoff equations one can show that under condition

$$T_2^{-1} = \frac{1}{2}\mu_0 \eta Q |M_z|,$$

<N. Blombergen and R. Pound, Phys. Rev., 95, 1954, 8].

where μ0 and η are constants, Q is the quality factor and Mz is the nuclear magnetization, the resonant circuit, tuned on the nuclear Larmor frequency, has no losses.



The maser and superradiation were investigated in the papers below:

See about SR: ➔

P. Bösiger, E. Brun, D. Meier, Phys. Rev. Let, **38**, 602 (1976);

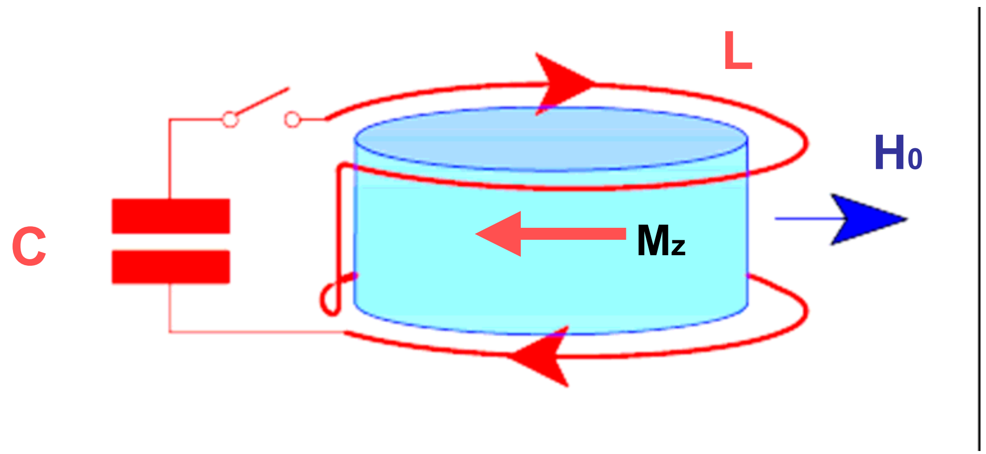
P. Bösiger, E. Brun, D. Meier, Phys. Rev., A **20**, 1073 (1979);

Yu.F. Kisselev et al., Zh. Eksp. Teor.. Fiz., **94,** 344 (1988);

L.A. Reichertz et al., Nucl. Instr. And Meth., A 340, 278 (1994).

Maser and superradiation phenomena

Since the circuit consists of the capacitance and a lossless superconductive loop, it must generate the rf-current when a magnetic flux through the loop is varied.



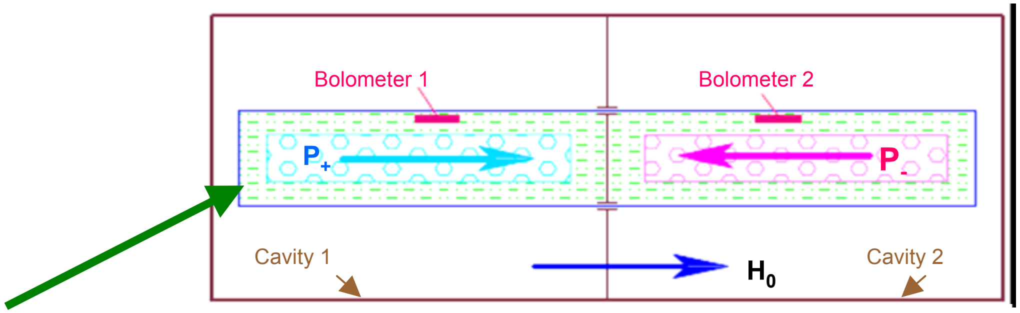
Such a supersensitive flux receiver allows to study the fundamental problem: what is the origin of spin oscillations. This discussion was started by Prof. Yukalov et al..

See: V.I. Yukalov, Phys. Rev., B 71, (2005), 184432 and references over there.

Detection of the electromagnetic radiation by negatively polarized nuclei at low magnetic fields

To understand more about spin oscillations, Let's consider the COMPASS 2001-2004 experiment

(SPIN-2004, Trieste, Italy, Y. Kisselev et al., p. 816.)

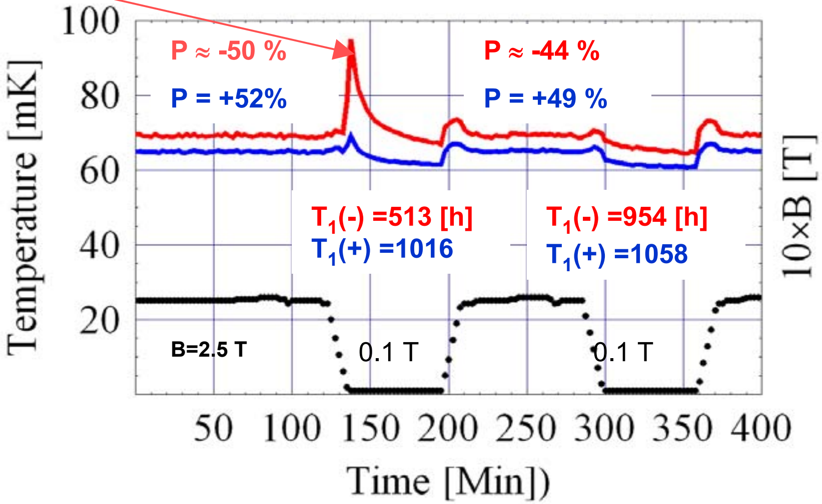


3He/4He mixture, T = 70 mK

Detection of the electromagnetic radiation by negatively polarized nuclei at low magnetic fields

This signal demonstrates the radiofrequency radiation emitted by the negatively polarized target material

Probably this radiation is a reason why the negative polarization in LiD is lower then the positive one,
P= + 57 % and P= - 52 %

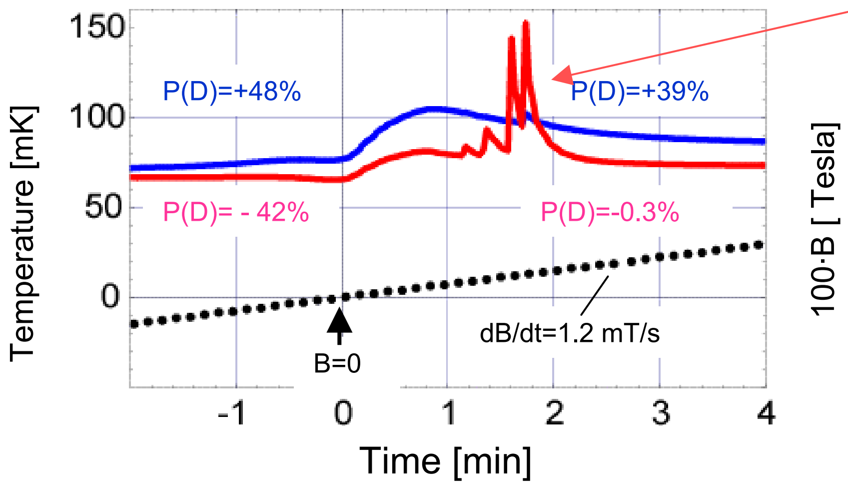


$$T_2^{-1} = \frac{1}{2}\mu_0 \eta Q |M_z|,$$

Blombergen and Pound formula valid for Zeeman spin sistems but DNP-mechanism also incorporates Dipole-Dipole interaction between nuclear and electron spins.

Detection of the electromagnetic radiation by negatively polarized nuclei at low magnetic fields

The radio-frequency radiation becomes spectrally resolved by changing of the magnetic field from -2.5 T to about +0.15 T.



Here you can see the coherent radiation of D and Li_7 obtained on the COMPASS polarized target at CERN

This is the first observation of the spectrally resolve resonant radiation emitted when the nuclear Larmor frequency falls within a range of characteristic frequencies of the electron dipole-dipole reservoir.

SUMMARY

The report surveys the further properties of highly polarized nuclear systems:

1 Frequency modulation effect and the distortions of the NMR lineshape promote a further development of the polarized target technique.

2 Maser and superradiation phenomena contribute to the development of quantum statistical physics; they are also serving as unique models for the applied synergetic.

3 It was demonstrated that the electromagnetic radiation from LiD shortens both the relaxation time and the ultimate value of negative deuteron polarization.

4 It was shown that the spectrally resolved selfradiation of spins detected “in-situ” at the very low magnetic field is interesting for further investigations as well as for practical applications in the nuclear spectroscopy.