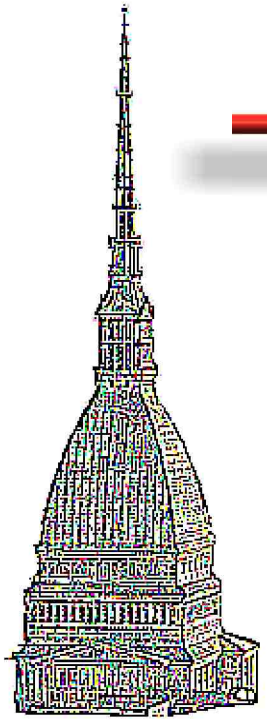

2nd Conference on Field Cycling NMR Relaxometry

Techniques, Applications, Theories

Torino (Italy)
June 1-3, 2001

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Contents

The ***First symposium on Field Cycling NMR Relaxometry*** was held in Berlin 1998, with the purpose of

- bringing together all the researchers practicing FC methods with those who do not yet but are interested in applying this technique in the future
- forming a discussion forum promoting and cultivating the description of molecular motions in complex system by spectral densities in relation to recent condensed matter theories and
- dissemination of the information on the technique as well as the potential of its applications

and it proved to be a big success.

This meeting is a continuation of the first symposium with an aim of strengthening the interaction between the FC users, making possible the exchange of new ideas or techniques and if possible forming an electronic discussion forum (FCNMR information server) etc.

The symposium will consist of lectures and poster presentations on the following topics

- Techniques
- Diamagnetic biosystems
- Magnetic Resonance Imaging
- Paramagnetic biosystems and level-crossing experiment
- Polymers and liquid crystals
- Porous media and surface systems

Organizing Committee:

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Language:

The official language of the Symposium will be English

Internet web page: http://nmr.ch.unito.it/meeting/ffcrelax

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The Organizing Committee of the Symposium would like to thank the following sponsor whose financial support is gratefully acknowledged

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Program

Friday: 1st June 2001

12.00	Registration	
12.45	Lunch	
14.00	Redfield A.	Two completely different shuttle experiments: PQR; and NMRD/NOE enhancement in a 500 MHz commercial high resolution NMR
14.35	Desvaux H	Sampling spectral densities in the KHz-MHz range by resorting to off-resonance rf irradiation in high magnetic field NMR spectrometer
15.10	Seliger J.	Magnetic field cycling study of ^{17}O NMR in short hydrogen bonds
15.45	Coffee Break	
16.15	Desreux J.F.	Nuclear magnetic relaxation dispersion and radiochemistry
16.50	Apih T.	Relaxometry of fast setting cements
17.25	Levitz P.	Water Dynamics in vycor porous glass as probed by NMRD: connection with the pore morphology
18.00	Kimmich R.	Proton and neutron field-cycling NMR relaxometry of liquids in porous media: Levy walks and surface topology
18.35	Poster Session	
20.00	Bus leaving for the Conference Dinner (Restaurant "De Filippi" – Bussolino di Gassino, Torino)	

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9.00	Korb J.P.	Low-frequency localized spin-dynamical coupling in proteins
9.35	Anoardo E.	Experimental and conceptual consideration about NMR relaxation parameters
10.10	Stepisnik J.	Molecular Transport in a porous media by the pulse-gradient-spin-echo spectral analysis
10.45	Coffee Break	
11.15	Privalov A. F	Spin-lattice relaxation dispersion in a superionic conductor
11.50	Satheesh V.	PMRD investigation of a low viscosity liquid crystal
12.10	Bryant R. G	High resolution magnetic relaxation dispersion by sample
13.00	lunch	

14.00	Luchinat C.	$^{1}H/^{17}O$ field dependent relaxation data to investigate hydration of proteins and aqua ions
14.35	Denisov V.	Water NMRD from solution of native and modified BPTI
15.10	Horsewill A.J.	Applications of the field cycling NMR to the study of molecular tunnelling
15.45	Coffee Break	
16.15	Vilfan M.	Shape fluctuation of membrane vesicles studied by NMR relaxometry
16.50	Fries P.H.	Theoretical interpretation of the 1H nuclear magnetic relaxation dispersion due to the relative motion of the repulsive $(CH_3)_4N^+/Gd(D_2O)_8^{3+}$ ion pair in heavy water
17.25	Lurie D.J.	Recent developments in Field Cycling MRI - Free radicals and Quadrupole Dips
18.00	Time for Posters	
20.00	Dinner	

Sunday 3rd June 2001

9.00	Helm L.	Combined analysis of NMR and EPR Relaxation data of Gd(III) chelates in aqueous solution
9.35	Vander Elst L	High Field Relaxivities of Dy-complexes: the Effect of the Water Exchange Rate
10.10	Powell H.	Water dynamics in Gd^{3+} exchanged zeolite Y
10.45	Terreno E.	Field Cycling Relaxometry: A Very Helpful Tool for Understanding the Relaxation Mechanisms of Paramagnetic MRI Contrast Agents
11.20	Coffee Break	
11.45	General Discussion & Closing Remarks	
13.00	Lunch	

Detailed Contents

Oral Communications

Two Completely Different Shuttle Experiments: PQR; and NMRD/NOE Enhancement in a 500 MHz Commercial High Resolution NMR.

A. G. Redfield

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First I will give a final report on our PQR project (Ivanov and Redfield, Zeit. Naturforsch. 53a, p. 269 (1998); also, First Berlin Workshop, 1998). Fast proton relaxation, and weak dipolar coupling, frustrated our original strategy. We finally found ^{11}B signals of boronic acid inhibitors bound to proteases using a simple H to ^{11}B cross polarization, followed by a two stage shuttle and field switch to zero field and back, with ^{11}B direct observe at 11.7 T. A relatively short RF search pulse at or near zero field showed PQR dips diagnostic for a tetrahedral aduct. The second part of my talk summarizes my project to replace the upper barrel of a standard 500 MHz instrument with a shuttler to move a standard 4 mm NMR tube from the center of a commercial 500 MHz instrument and 5 mm probe, up to the fringe field, to permit a R_1 or NOE mixing interval to be programmed within any sequence. This somewhat repeats previous work (1); the main problems are: to be able to install and remove the entire equipment from the spectrometer within an hour; to not break the probe or sample tube; to have easy operation with temperature control and performance monitoring; and to reduce vibration and bounce acceptably. The shuttler will be nearly complete in May, but may not yet be tested in a spectrometer. See my web site (search Brandeis University) for an up-to-date detailed report on its construction.

1. Wagner et al., JMR 140, p. 172 ('99); Wu and Johnson, JMR 116, p. 270 ('95); Kerwood and Bolton, JMR 75, p. 142 ('87).

Sampling spectral densities in the kHz-MHz range by resorting to off-resonance rf irradiation in a high magnetic field NMR spectrometer

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In the rotating frame, the presence of an rf irradiation of frequency ω, shifted out of resonance by an offset Δ, defines, for the spins, an effective field which is tilted by an angle $\theta = \arctan(\omega_1/\Delta)$ relative to the static magnetic field direction. By varying the rf field amplitude ω_1 and the offset Δ, one can continuously vary (i) the angle θ from the longitudinal conditions (θ=0°) to the transverse ones (θ=90°), but also (ii) the effective field amplitude $\Omega^2 = (\Delta^2 + \omega^2)$. As a consequence of this double modulation, the relaxation rates of the spin components aligned with this effective field axis depend on the spectral density values at 0, $n\omega$ and $p\Omega$ frequencies. Due to the large range of ω_1 and Δ values which are experimentally available, the approaches based on the study of relaxation in the presence of an off-resonance rf irradiation allow the obtaining of many measurements, which are relied by well-defined equations. This can be used to improve the accuracy of the determination of the physically relevant parameters.

In this presentation we shall concentrate on the smaller frequencies (terms dependent on $p\Omega$), that is the detection and characterization of motions occurring in the micro to millisecond time scale. Two types of relaxation mechanisms will be considered: (i) dipolar relaxation as an example of an interaction presents in all the range of frequencies and (ii) fast chemical exchange, which only contributes in the low frequency range and requires high static magnetic fields to enhance its effects. We shall show that the information on the spectral density functions can be accessed not only by determining the relaxation rates, which is rather time consuming, but also by measuring the steady-state magnetization in the presence of an off-resonance rf irradiation. The advantages of this alternative method will be discussed.

See for a review on this field:
H. Desvaux and P. Berthault, *Prog. NMR Spectrosc.*, **35**, (1999), 295-340.

MAGNETIC FIELD CYCLING DOUBLE RESONANCE STUDY OF SOME SHORT INTRAMOLECULAR HYDROGEN BONDS

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^{17}O nuclear quadrupole resonance (NQR) spectra have been measured in naturally aboundant dibenzoylmethane, benzoylacetone, acetylacetone and pyridine-2,3-dicarboxylic acid by a highly sensitive ^{1}H-^{17}O nuclear quadrupole double resonance technique based on magnetic field cycling.

In dibenzoylmethane we observe two non equivalent oxygen positions. The O-H...O hydrogen bond is thus asymmetric. The asymmetry increases with decreasing temperature. The sum of the O-H and O...H distances as determined from the dipolar structure of the NQR lines is less than the hydrogen bond length. This is characteristic for a dynamic proton disorder O-H...O $\leftrightarrow$ O...H-O.

The two oxygen positions in an O-H...O hydrogen bond in benzoylacetone are only weakly non equivalent. No significant change in the asymmetry of the hydrogen bond is observed on cooling the sample from room temperature to 173 K. The two proton-oxygen distances in a hydrogen bond are equal within the experimental resolution. Their sum is similarly as in dibenzoylmethane less than the hydrogen bond length what again shows the presence of a dynamic proton disorder.

In acetylacetone we observe only one oxygen position in the temperature interval between 150 K and 200 K. The hydrogen bond is thus symmetric within the experimental resolution. The proton-oxygen distance as determined from the dipolar structure of the NQR lines is equal to (0.118±0.002)nm what is less than one half of the hydrogen bond length. The symmetry of the hydrogen bond is thus associated with proton jumps between two equivalent equilibrium positions.

In pyridine-2,3-dicarboxylic acid with a rather short O-H...O hydrogen bond we observe two non equivalent oxygen positions. The hydrogen bond is thus asymmetric. No measurable change of the asymmetry occurs on cooling the sample from room temperature to 173 K. The sum of the two proton-oxygen distances, (0.117±0.01)nm and (0.121±0.02)nm, is within the experimental error equal to the length of the hydrogen bond. Proton is thus located in an off-center single potential well.

The present experimental results are compared to the results of a previous analysis of ^{17}O NQR parameters in C-O-H...O=C hydrogen bonds.

Nuclear magnetic relaxation dispersion and radiochemistry

Jean F. Desreux, Bernard Lambert and Vincent Jacques

Coordination and Radiochemistry, University of Liège, Sart Tilman B6, B-4000 Liège, Belgium, jf.desreux@ulg.ac.be

Nuclear magnetic resonance is not often used to study radioactive materials because of its poor sensitivity and because few spectrometers dedicated to such studies are available.. A sizeable gain in sensitivity is reached by measuring nuclear magnetic relaxation dispersion (NMRD) curves because the properties of the much more abundant solvent molecules are investigated rather than directly those of the dissolved material.

NMRD curves afford useful information relating to the electronic distribution of the metal ions, their hydration state, the dynamic behavior of their complexes and their aggregation state. Competition experiments yield information on relative stability and formation of mixed complexes. All these information are of interest in radiochemistry. Three applications of NMRD will be discussed: a) the magnetic properties of some actinides, for instance curium (III), b) the interactions of *f* elements with humic acids and the migration of radionuclides, c) the analysis of extraction systems based on macrocyclic ligands.

Relaxometry of Fast Setting Acid-Base Cements

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Proton nuclear magnetic relaxometry is a well-established technique for continuous and nondestructive monitoring of hydration of conventional Portland building cements[(1-5)]. Here we demonstrate the feasibility of nuclear magnetic resonance (NMR) monitoring of the setting reaction of fast setting acid-base cements, such as glass-ionomer cements (GIC), resin modified GIC and zinc-phosphate cements (ZPC). Like in the case of conventional Portland cements, the setting reaction that results in hardened cement is here initiated by mixing a liquid with powder, but the studied families of cements harden in minutes as compared to days in the case of Portland cements. Due to convenient working time, good mechanical properties, bio-compatibility and aesthetic properties, this materials find their dominant use in dentistry.

In the experiments, the spin-lattice relaxation time T_1, the inverse linewith T^*_2 and the intensity of the signal were measured as functions of the setting time.

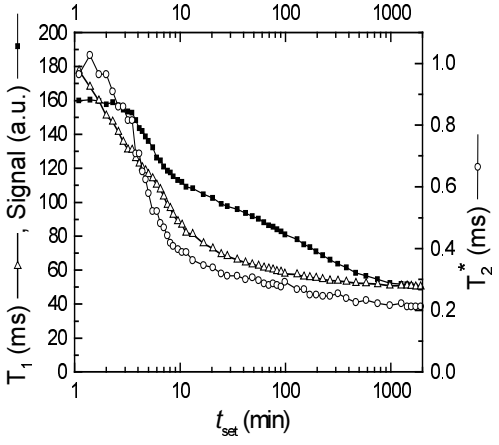

Fig. 1
Setting time dependence of the spin-lattice, the spin-spin relaxation time and the "liquid" signal intensity for KetacCem glass-ionomer cement.

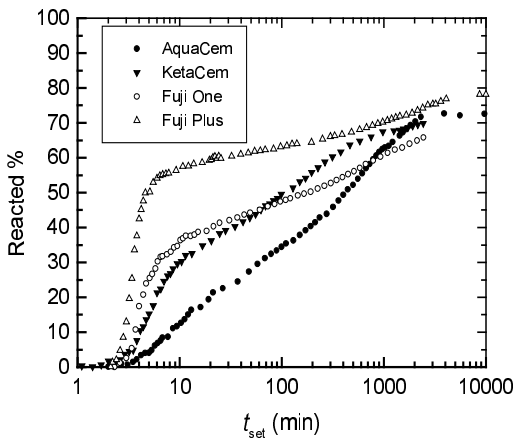

Fig.2
Reaction percentage, defined as the relative amount of the remaining liquid signal for the four GIC samples investigated.

The decrease of relaxation times during the setting reaction in **glass-ionomer cements** (Fig. 1) was found to be compatible with the Portland cement results[1-5], where due to the fast exchange between the slowly relaxing bulk water protons and the rapidly relaxing protons of the water molecules in the surface layer, the average relaxation rate is determined by the cement paste surface to volume ratio.

On the other hand, and in contrast to previously published NMR studies of setting Portland cements, where a decrease of spin-lattice relaxation time is attributed to enhanced relaxation at the growing internal surface, the spin-lattice relaxation time T_1 was found to *increase* during the set of clinically used **zinc phosphate cement.**

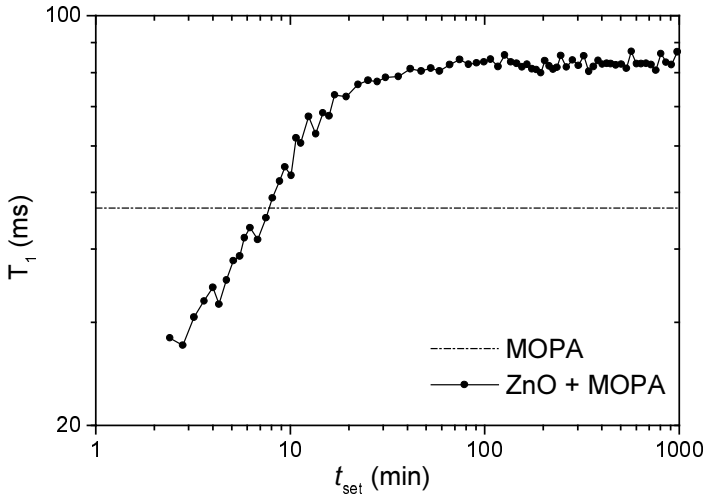

Fig. 3. Setting time dependence of T_1 in zinc-phosphate cement.

Comparison with a detailed study of self-diffusion coefficient, viscosity, and magnetic filed dispersion of T_1 in pure and aluminum modified orthophosphoric acid demonstrated that the increase of T_1 during the setting of zinc-phosphate cement is connected with the increase of molecular mobility in the residual phosphoric acid solution. Although not taken into account so far, such effects may also significantly influence the relaxation times in setting Portland cements, particularly when admixtures with effect on water viscosity are used.

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3. W. P. Halperin, J.-Y. Yehng, and Yi-Qiao Song, *Magn. Res. Imag,* **12,** 169 (1994)
4. T. Apih et al., Cement and Concrete Research **31**, 263 (2001)

WATER DYNAMICS IN VYCOR POROUS GLASS AS PROBED BY NMRD: CONNECTION WITH THE PORE MORPHOLOGY.

P. Levitz1, J.P. Korb1, A. Van Quynh1,2, S. Godefroy1, and R.G. Bryant2
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Mesoscopic media such as mesoporous materials develop large specific surface area. These matrices can be filled with liquid and the interfacial region between the solid matrix and the pore network strongly influences the molecular dynamics of the embedded fluid. The confinement might influence the molecular dynamics on a length scale ranging from 1 nm up to several mm . At short times t and small distances r ($t < 1$ ns, $r < 3$ nm), neutron spin echoes or quasi elastic scattering can be used to follow local molecular dynamics inside the pore network or nearby the interfacial region. At very long times and large distances (above 1 ms and 1 mm), macroscopic experiments or NMR pulsed field gradient spin echo experiments are currently used. At the mesoscopic scale, few tools provide insight to how homogenization and up scaling are done. An interesting way to probe these mesoscopic scales is to look at the dispersion of the nuclear spin-lattice relaxation rate of the liquid molecule using field cycling NMR relaxometry. NMR dispersion (NMRD) provides a remarkable opportunity to follow the relaxation rate over a large range of Larmor frequencies, mainly from 10 kHz to tenths Mhz.

We have performed such an experiment on a fully hydrated porous Vycor glass. In order to understand the relationship between geometric disorder, interfacial confinement, and NMRD, we have computed an off-lattice reconstruction of the Vycor glass This model agrees with available experimental data (specific surface, porosity, chord length distributions, small angle scattering and tortuosity). A Brownian dynamics simulation was performed to compute long time molecular self-diffusion and NMRD data. Experimental data are well reproduced and appear to be connected with the translation diffusion of water near the internal surface of the porous Vycor glass. Several other multiconnected interfacial structures, such as periodic minimal surfaces (as found in the case of MCM48), were investigated and exhibit a different NMRD evolution. Therefore, NMRD appears to be selectively sensitive to the interfacial geometry of these mesoscopic and some time disordered porous materials. Possible extension to some other mesoscopic divided media such as colloidal systems or pastes will be discussed.

PROTON AND DEUTERON FIELD-CYCLING NMR RELAXOMETRY OF LIQUIDS IN POROUS MEDIA: LÉVY WALKS AND SURFACE TOPOLOGY

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^{1}H and ^{2}H field-cycling NMR relaxometry and field-gradient ^{1}H NMR diffusometry methods were applied to liquids in porous media such as porous silica glasses, fineparticle agglomerates (ZnO, TiO_2, Al_2O_3), saponite, and lipid bilayer dispersions (1). The typical dimensions of the pore spaces ranged from 1 to several 100 nm.

At temperatures below the freezing point of the liquids in the pores, one to two molecular diameters thick surface layers remain unfrozen. Molecular dynamics in these nonfreezing surface layers (NFL) were also studied. Confinement of the liquid adsorbate to the pore space or, in frozen samples, to the NFL reduces the diffusion coefficient mainly due to the geometrical restriction. In the case of NFL, the reduction amounts to one order of magnitude relative to the bulk values.

Pronounced differences of the spin-lattice relaxation dispersion were found for polar and nonpolar adsorbate species (2). This finding reflects the limits of "weak" (nonpolar species) and "strong'" (polar species) adsorption (3). In the latter case, the correlation times of the adsorbate orientation are up to eight orders of magnitude longer than in bulk. The low-frequency spin-lattice relaxation dispersion is explained on the basis of "reorientations mediated by translational displacements" (RMTD) of adsorbate molecules on the surfaces (4).

The propagators relevant for translations along surfaces are different depending on whether the sample is frozen or not. In the case of the topologically two-dimensional NFL, the low-frequency spin-lattice relaxation data can well be described using an ordinary Gaussian displacement distribution function for two-dimensional diffusion.

This is in contrast to the unfrozen samples in the strong-adsorption limit, where the low-frequency data are governed by a Lévy walk surface diffusion process. In the strong-adsorption limit, bulk-mediated surface diffusion (BMSD) was predicted as a mechanism so that Lévy walks with a Cauchy propagator follow in the short-displacement limit instead of an ordinary Gaussian function (4).

The orientational structure factor formalism of the RMTD mechanism originally derived for ordinary diffusion is generalized to Lévy walks. This permits us to distinguish the influences of surface diffusion and of the surface geometry on the spin-lattice relaxation dispersion. The diffusion propagators relevant in the frozen and unfrozen samples can thus directly be compared. A marked difference was found.

A computer simulation of a random walker in the vicinity of strongly adsorbing surfaces confirms these conclusions (5). In particular a superdiffusive mean-squared displacement behaviour was found in the short-time limit as predicted by the BMSD formalism (3).
The same proton and deuteron field-cycling relaxometry techniques were also applied to hydration water in lipid bilayers (6). In the so-called ripple phase of such dispersions, the

lipid/water interface is undulated with a quasi-static "wavelength" of 12 to 14 nm. Water molecules effectively diffusing along such a corrugated surface show a correspondingly modulated deuteron spin-lattice relaxation dispersion. It is shown that the motional narrowing of the water deuteron line splitting can be explained consistently with the spin-lattice relaxation dispersion. Furthermore, the undulation wavelength fitted to the experimental data reproduces the literature value found with scanning tunnel microscopy. The field-cycling relaxometer used for the deuteron measurements is described in Ref. (7).

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Low-frequency Localized Spin-Dynamical Coupling in Proteins

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We show that the magnetic field dependence of the proton spin lattice relaxation rates 1/T1 = Aw0-b in non-crystalline proteins may be quantitatively related to structural fluctuations localized along the backbone that modulate proton-proton dipolar couplings. The parameter A is related to the temperature, the dipolar coupling strength and the energy for the highest vibrational frequency in the polymer backbone. The parameter b is related to the fractal dimensionality of the spatial distribution of protons and the spectral dimensionality that characterizes the anomalous diffusion. Extension of the theory is presented to treat the case of hydrated proteins. This theory is satisfactorily compared with field cycling experiments realized on lysozyme protein.

EXPERIMENTAL AND CONCEPTUAL CONSIDERATIONS ABOUT NMR RELAXATION PARAMETERS

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Since the original formulation of Bloch equations, relaxation properties of nuclear spins in matter turned to be of high interest for the study of different physical situations. Forthcoming theories of NMR relaxation were aimed to establish a connection between the phenomenological relaxation parameters and the microscopic phenomena driving the relaxation process. The semi-classical approach is usually discussed in the *motional narrowing* limit, and the well known expressions for the relaxation parameters in terms of spectral densities is evoked [1]. Sometimes, these expressions are used regardless of the validity of the original physical assumptions made to get them. Within these assumptions, the semi-classical theory "for liquids and gases" assumes a weak order of the spin-system, a random fluctuation of the interaction and a dominant Zeeman energy for the spins (at the end, this theory represents the picture of a single spin immersed in a fluctuating magnetic field). Such conditions, in principle fulfilled by liquid and gases at high magnetic fields, may not be wholly satisfied in other physicochemical systems where collective or slow and/or anisotropic motions are present. This situation can be relevant, for example, when dealing with relaxation experiments at low fields, like those implemented with the aid of field-cycling (FC) techniques. We know that a relaxation parameter can be dependent on the observed time scale, and we associate the resulting dispersion with the molecular mobility *indirectly* through the fluctuations that such motions produces in the dipolar, quadrupolar, etc. interactions. Therefore, it is important to ensure that the used model is really fitting with the physical situation of interest.

A second point that must be addressed is the presence of false dispersions of the observed relaxation parameter. In FC experiments, this situation becomes critical if the evolution field is switched down close to the average local fields. In such a case, unless the adiabatic cycle is ensured, undesirable effects are guaranteed. A similar situation arises in the rotating frame when the amplitude of the lock field matches average local fields. A point of particular interest related with FC Relaxometry is the presence of the so called "low frequency plateau", typically present in the dispersion profiles of viscous and anisotropic fluids, polymers and soft matter [2]. In this context, it is important to determine the real origin of the plateau, and to decide when this plateau could be masked by a false dispersion or not. In such situations, other experimental techniques can be used to get additional information, like the dipolar correlation effect [3], or T_2 (spin-spin relaxation time) dispersion as a function of pulse timing in a CPMG (Carr-Purcell-Meiboom-Gill) experiment [4].

Other important aspect to consider is the information that each relaxation parameter provides when used to explore identical time scales. As an example, we can compare the $T_{1\rho}$ dispersion (spin-lattice relaxation parameter in the rotating frame) with the T_1 FC dispersion within an overlapping frequency band. While both parameters can provide the same information if the

relaxation in the observed frequency range is driven by isotropic motions [5], it could not be the case under the presence of highly correlated and/or collective motions [6]. Alternatively, the study of the Larmor frequency dependence of the dipolar relaxation parameter T_{1D} as implemented by a combination of the Jeener-Broekaert pulse sequence with FC [7,8], provides important complementary information.

The aim of this communication is to present a general discussion on these topics, with a mayor emphasis in the last aspect. The discussion will be particularized to selected examples.

The author thanks the Alexander von Humboldt Foundation for financial support during the scientific stay at the University of Ulm – Germany.

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MOLECULAR TRANSPORT IN A POROUS MEDIA BY THE PULSE-GRADIENT-SPIN-ECHO SPECTRAL ANALYSIS

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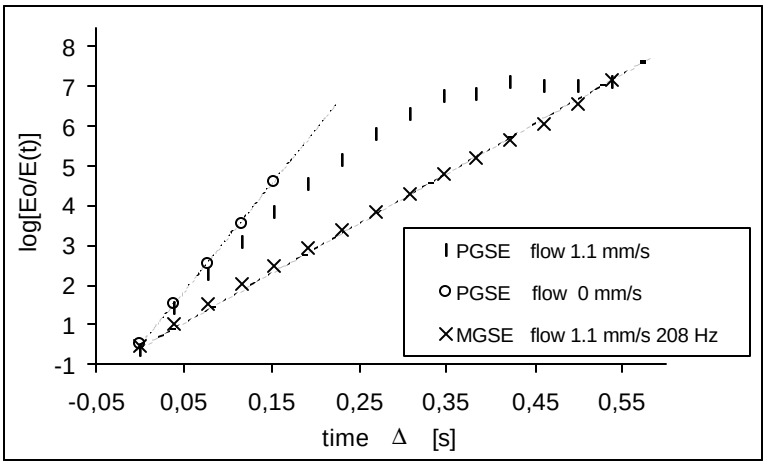
The measurements of diffusion in the porous media by the modulated gradient spin echo method (MGSE) reveal strong dependence of spin echo attenuation on the velocity self-correlation spectrum of entrapped molecules[1]. This method takes an advantage of the relation between the spectrum of molecular motion and the spectrum of spin phase modulation created by gradient spin echo sequence. We show that for the gradient sequence with the two pulses (PGSE) it brings about, in some other way, known $\sqrt{D\Delta}$ early time dependence of spin echo decay. While at intermediate times, it provides the $D\alpha\Delta + d[1-\exp(-\Delta/t_r)]$ dependence, and leveling into asymptotic time-independent attenuation when displacements are larger than the size of compartments. The measurement of water in the system of packed polydispersed beds (0.1-0.03 mm) clearly shows that the flow-induced turbulences of imbibed water shorten the time-of-flight between boundaries t_r so that a distinction between these three regimes can be seen. Here the effect of internal gradients due to the susceptibility difference of the heterogeneous structure has been removed by a specially modulated gradient sequence that has identical zero-frequency peak in the dephasing spectrum as the pulse gradient sequence and, consequently, the same evolution of signal decay. This spectral analyses demonstrates that the PGSE with low $q = gDd$ can provide information about the parameters of porous structure, like the average pore size d and the tortuosity α, and so reveal the long-range structure of porous media, particularly when used in combination with the methods of modulated gradient spin echo. Figure shows the PGSE attenuation of stationary and trickling water (velocity 1.1 mm/ s) through porous structure. The MGSE attenuation[1] is given for comparison to demonstrate its clear linear rise at same flow velocity.



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SPIN-LATTICE RELAXATION DISPERSION ANALYSIS IN A SUPERIONIC CONDUCTOR

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By analyzing the spin-lattice relaxation dispersion in systems with magnetic dipolar interactions undergoing mutual diffusion one obtains information on spectral density functions. In disordered systems one often observes a superposition of spectral density functions. The determination of the contributions from the relaxation data is a complicated ill-posed problem. In our sample of superionic LaF_3, which contains several disordered motional modes, a model free analysis does not apply. Nevertheless, spin-lattice relaxation dispersion can be useful since a motional model is known from the ^{19}F NMR line shape analysis. Two dynamic modes, a fast and a slow one, are identified for different structurally unequivalent fluorine sublattices. Both motional processes are found to be “non Debye like” obeying a log-Gaussian distribution of correlation times. The sensitive time scale of our relaxation dispersion analysis lies in the frequency range of 50 kHz ÷ 400 MHz corresponding to correlation times ranging from 10^{-5} s to 10^{-10} s, thus overlapping and extending the line shape analysis time scale (10^{-4} s to 10^{-6} s). Thus we are able to approve a previously suggested model and to extend it to much higher temperatures.

The measurements are carried out using a home built fast field-cycling relaxometer [1]. The polarization field ranges from 10^{-5} T up to 1 T, the detection field is 1 T, the switching time is 5 ms without and 0.2 ms with an active switching circuit. The inhomogeneity over the sample volume is 30 ppm. The accesible temperature range is 200 K ÷ 1400 K. In this field cycling spectrometer we thus span a frequency range from 50 kHz to 40 MHz. In combination with a standart NMR we presently cover frequencies up to 400 MHz.

The combination of NMR line shape studies and relaxometry widely enlarges our dynamic range up to the neutron scattering regime. Corresponding experiments are in preparation.

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PMRD Investigations of a Low Viscosity Liquid Crystal

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Magnetic Relaxation Dispersion (MRD) is a well established technique to study molecular motions in liquid crystals. Recently several single component liquid crystals as well as liquid crystalline mixtures were studied using this technique[1]. It is shown that MRD technique can be used to obtain detailed information regarding the anisotropy in elastic properties as well as the presence of smectic clusters in nematic phases[1-3]. These studies have also brought out the difference in the nematic phases with and without an underlying smectic phase. Observation of an interesting nematic state having smectic seeds but unable to undergo a transition into a smectic state due to isotropic elastic properties of the medium[3] is another result of these investigations. All these systems studied so far have medium viscosity (bulk viscosity, h, about 0.5 Poise) and elastic properties in the range of 10^{-6} dynes. However there are several liquid crystals having much lower viscosity and such systems have been attracting considerable interest due to a number of applications. So far there are no MRD investigations of low viscosity systems and it should be rewarding to investigate the nuclear magnetic relaxation dispersion behavior of such systems.

Liquid crystalline isothiocyanates have several applications as single component systems as well as mixtures, owing to their wide nematic range, low viscosity with weak temperature dependence and good chemical stability[4]. Consequently isothiocyanates as well as their mixtures were subjected to a variety of investigations to study their dielectric properties, optical anisotropy, visco-elastic properties, display dynamics, etc.[4,5] This report presents the results of proton magnetic relaxation dispersion (PMRD) investigations of 6CHBT in its nematic phase.

PMRD data were collected on 6CHBT at two temperatures (22 and 33°C) using a Field Cycling NMR spectrometer (10 kHz – 10 MHz; Stelar Spinmaster FFC2000) and a pulsed NMR spectrometer (3 MHz – 40 MHz). The errors in the data vary from 2% (at low frequencies) to 3% (at high frequencies) and the temperature stability is within 0.2°. The data were analyzed considering nematic director fluctuations (DF), molecular self-diffusion (SD) and reorientation (R). The DF contribution takes into account possible anisotropy in elastic properties (Frank elastic constants $K_1 \neq K_2 \neq K_3$) as well as upper and lower cutoff wavelengths of the DF modes. K_1, K_2 and h are fixed at values reported earlier, and K_3 and cutoff wavelengths are allowed to vary in the data analysis.

Figure 1 shows the results of this analysis at 33°C. The results indicate that DF and R essentially dominate the proton relaxation in the entire frequency range. The results also show classical $\omega^{-0.5}$ dependence to DF contribution (R_{1DF}) in the frequency range studied, indicating that the

cutoff frequencies are well outside this range. This corresponds to the presence of no smectic clusters. This is consistent with the fact that 6CHBT shows a stable nematic phase without underlying smectic phase. The value of K_3 deduced from the frequency dependence of R1DF is consistent with the earlier reported data[4,5]. The temperature dependence of the reorientation correlation time that is deduced from the corresponding contribution (R_{1R}) shows consistent variation.

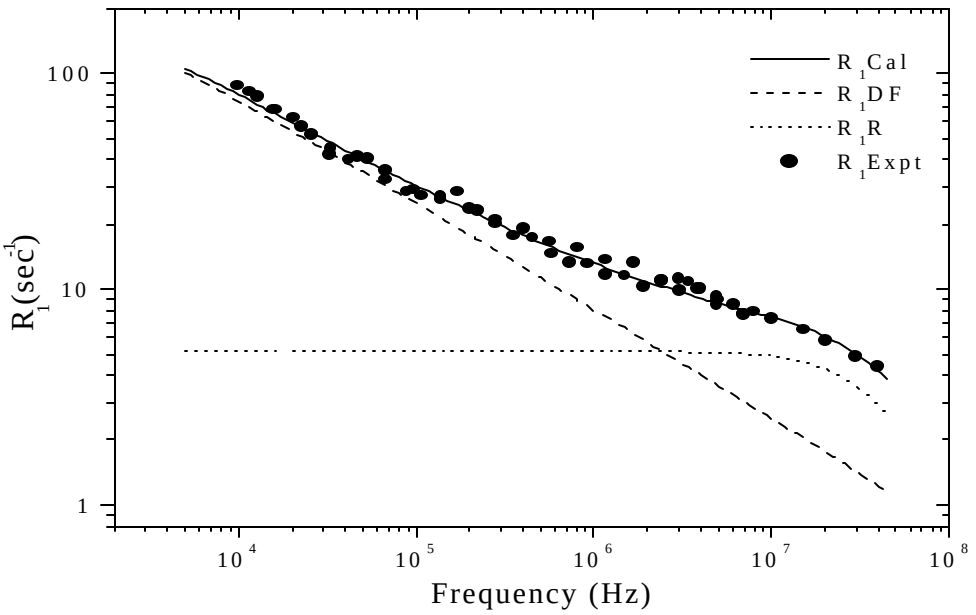

Figure 1: PMRD data in 6CHBT at 33°C

To conclude, present studies show that the DF contributions spread to considerably high frequencies in a low viscosity nematic like 6CHBT. SD contribution to relaxation is very small, indicating fast diffusion, whereas molecular reorientations dominate the relaxation mechanism at high frequencies. These PMRD investigations of an otherwise well studied 6CHBT show a good agreement between the elastic coefficients deduced from NMR data and those reported earlier, validating the applicability of this techniques to low viscosity liquid crystals as well.

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High Resolution Magnetic Relaxation Dispersion by Sample Shuttling

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Besides its many advantages, the current switched magnetic relaxation dispersion spectrometer offers limited sensitivity and low resolution. One solution to these problems is to employ two magnets that are magnetically shielded from each other and to move the sample rapidly between them. We have constructed such a spectrometer employing a 7 T superconducting magnet to provide the polarization and detection fields, and an iron core variable field magnet housed in an iron shield but in close proximity to the high field. The resolution routinely obtained in the detection field is 7 Hz on protons, but is limited more by probe design than by inherent limitations in the magnet or shims. The sensitivity is excellent permitting routine study of solute species.

The major disadvantage of the design is that the finite shuttle times limit the maximum rates that may be measured. In many cases, careful experimental design may circumvent this problem so that interesting dynamical information may be obtained.

The sensitivity gains permit magnetic relaxation dispersion measurements to be made dilute solute species, and several resonances may be observed simultaneously. In simple protein solutions, this spectrometer permits study of dilute protein solutions in the concentration range where fluorescence depolarization measurements have been typically made. Under these conditions, if oxygen is excluded from the samples, the protein induced relaxation dispersion profile is Lorentzian and the inflection point corresponds to a rotational correlation time identical with that obtained from fluorescence measurements. The high field tail above the rotational dispersion is essentially eliminated by removal of oxygen, which causes a translational contribution to the relaxation with a correlation time of order 7 ps.

Multinuclear MRD provides new opportunities for defining solute-solute dynamics. ^{7}Li is a useful mimic of alkali metals that are important in biochemistry. We have studied the relaxation dispersion in DNA solutions and find that, when the DNA is long, the relaxation disperison is linear in the logarithm of the Larmor frequency. This field dependence generally indicates a 2-dimensional process dominates relaxation even though it may appear that diffusion along the charged rod represented by the DNA should be a one-dimensional problem. Similar results are found for the methyl protons in tetramethyl ammonium ion. Both results may be understood in terms of transient binding interactions with sites on the DNA coupled with rapid diffusion up and down the DNA strands coupled with chemical exchange between DNA strands.

The finite shuttle times limits the relaxation rates that may be measured accurately. This problem may be circumvented in many cases by diluting the relaxation rate with a chemical exchange event where a ligand exchanges between a site of high relaxation rate and one of low relaxation rate such as a protein site and the aqueous pool. By adjusting concentrations, the total relaxation rate of the ligand may be adjusted to a convenient value and the relaxation dispersion measured accurately. In the case that the relaxation is dominated by an electron-nuclear coupling, the electron Larmor frequency dominates the observable field dependence of the relaxation rate. For hemoblobin spin-labeled with a nitroxide at the cysteines (β-93), the acetate resonance provides a report of two high frequency processes with correlation times of 4 ns and 20 ps.

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$^{1}H/^{17}O$ field dependent relaxation data to investigate hydration of proteins and aqua ions

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Field dependence of water nuclei relaxation is a primary tool to investigate hydration of molecules in solution. Hydration water can be classified according to its residence time in the solute environment as well as according to its direct or indirect interaction with the solute itself. Some recent progresses in understanding the contribution of the various classes of water molecules to both aqua ions of transition metals and proteins/metalloproteins will be described. The focus will be on the hydration of chromium(III), for which extensive ^{17}O data were already available (A. Bleuzen, F. Foglia, E. Furet, L. Helm,* A. E. Merbach,* and J. Weber ; J. Am. Chem. Soc., 1996; 118(50)), revisited through proton NMRD, and on the hydration of cytochrome c, through both high resolution NMR and ^{17}O relaxometry. Some general considerations on the contribution to water NMRD from labile protein protons will also be made.

Water MRD from solutions of native and modified BPTI

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The Magnetic Relaxation Dispersion (MRD) technique is one of the principal methods used to study protein-water interactions in solution. Combination of ^{17}O and ^{2}H MRD data from protein solutions with high-resolution structures of BPTI and other proteins made possible quantitative interpretation of MRD profiles and elaborate description of protein hydration in terms of the amount of internal and surface water, orientational order of the internal water molecules, and the rates of hydrogen exchange between the bulk water and protein labile hydrogens [1,2]. Measurement of the temperature dependent ^{17}O and ^{2}H difference-MRD from solutions of BPTI and its G36S mutant led to the first precise determination of the residence time of an individual buried water molecule in a protein (W122 in BPTI, τ_{res} = 170 μs at 27 °C), which shed light on the protein conformational dynamics [3].

New MRD data are presented on another BPTI mutant, C14S/C38S, as well as on selectively reduced BPTI, in which the disulfide bridge 14-38 (one of the three in BPTI) is disrupted by mutation or chemical reduction. Since the 14-38 disulfide is spatially close to the most long-lived internal water molecule W122, the residence time of the latter was expected to reflect the influence of the bridge on the local protein dynamics. The temperature dependent MRD data show that W122 exchange with the bulk solvent becomes several orders of magnitude faster when the disulfide bridge is missing, i.e., its residence time falls in the same range (ns – μs) as for the other 3 internal water molecules in the protein, which proves that the 14-38 disulfide is an important constraint for the local unfolding dynamics in BPTI.

Longitudinal and transverse ^{1}H relaxation rates from protein solutions contain the (pH-dependent) contribution from fast-exchanging labile protein hydrogens, which can be used to extract information about the rates of their exchange with the bulk.

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Quantum Molecular Tunnelling studied by Field-Cycling NMR

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When the interchange between two possible conformations of a molecule is governed by motion between energetically equivalent potential wells, the dynamics at low temperature are characterised by coherent tunnelling with a well-defined frequency. The tunnelling frequency is an exponential function of the height of the interceding barrier, the mass of the moving particles and the separation of the potential wells. When the potential wells have inequivalent energy, the motion can still proceed provided there is an interaction with external degrees of freedom to make up the mismatch in energy, for example the phonon bath. In this case the dynamics are incoherent and the motion is characterised by an inverse correlation time which is usually proportional to the square of a frequency determined by a tunnelling matrix element. This inverse correlation time also has an exponential dependence on the barrier properties.

Depending on the characteristics of the potential barriers in particular materials, the tunnelling frequencies and rates can possess values encompassing many orders of magnitude. To study these with conventional NMR at constant frequency severely restricts the information content; much better is a broadband approach which for practical reasons requires that field-cycling techniques are adopted.

Applications of field-cycling NMR to the study of coherent molecular tunnelling will be reviewed [1] including level-crossing and low-field NMR spectroscopy. Proton transfer in the hydrogen bond provides an example of incoherent molecular tunnelling and recent experimental data recorded in Nottingham will be discussed together with an appraisal of future prospects including the design of a superconducting field cycling magnet for the study of molecular tunnelling.

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Shape fluctuations of membrane vesicles studied by NMR relaxometry

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Lipid vesicles are suitable model systems for the study of structural and dynamical properties of biomembranes [1]. Their shape and functionality are determined by the bending elastic energy associated with the modulus κ and by the lateral tension in the bilayer σ. Measurements of κ have been performed using video microscopy [2], micropipetting [3], electric field deformation technique [4], and nuclear magnetic resonance (NMR) relaxometry [5,6]. In lipid bilayers fast internal and local reorientations of molecules dominate the relaxation in the MHz regime. These motions only partly average the anisotropic nuclear spin interactions because of orientational order of the molecules. The residual anisotropy is then modulated by slow collective fluctuations and by lateral diffusion of molecules along the curved surface. Marqusee, Warner, and Dill [7] calculated the nuclear spin relaxation rate due to out-of-plane fluctuations, i.e. undulations, of a planar membrane. They showed that the spin-lattice relaxation induced by planar membrane undulations depends linearly on the Larmor frequency, $T_1^{-1} \propto \omega^{-1}$, similarly as in thermotropic liquid crystals with a layered structure [8]. Such linear dispersion behavior was experimentally observed in the kHz frequency regime for oligo- and multi-lamellar dispersions of various lipids [5,6,9,10].

In this paper we consider the relaxation of nuclear spins in *unilamellar quasi-spherical vesicles*. The advantage of unilamellar vesicles over the stacks of membranes is the absence of inter-bilayer interactions which might diminish the contribution of undulations in the kHz frequency range [11], where this mechanism is expected to dominate the total relaxation rate. To calculate the effect of vesicle shape fluctuations on nuclear spin relaxation, the hydrodynamical model of Milner and Safran [12] is adopted. In this model a vesicle is considered as a quasi-spherical shell of radius R_0 with constant volume and fixed area which is larger than the area of the sphere with the same volume. If the deviations of the vesicle shape from the spherical conformation are small, the only important spectral density function in the local coordinate frame is $J_1(\omega)$

$$J_1(\omega) = \Re \int_{-\infty}^{+\infty} \left(\langle n_\theta(0) {n_\theta}^*(t) \rangle + \langle n_\phi(0) {n_\phi}^*(t) \rangle \right) \mathrm{e}^{-i\omega t} dt. \tag{1}$$

Here n_θ and n_ϕ represent the polar and azimuthal fluctuating components of the local normal to the bilayer, respectively. Taking into account the mean square amplitudes and the characteristic times τ_l of spherical normal modes as given in Refs. [12,13], we obtain

$$J_1(\omega) = \frac{k_B T}{4\pi\kappa} \sum_{l=2}^{l_{\max}} \frac{l(l+1)(2l+1)}{(l^2+l-2)(l^2+l+\sigma)} \frac{2\tau_l}{(1+\omega^2\tau_l^2)}. \tag{2}$$

The upper limit of summation, $l_{\max}$, is determined by the size of the molecules, $l_{\max} \approx \pi R_0/a$, where a is the average distance between neighboring molecules in the lateral direction. The lower limit is $l = 2$ since the $l = 0$ and $l = 1$ modes do not contribute to the relaxation. According to Eq. 2, $J_1(\omega)$ and consequently the nuclear spin-lattice relaxation rate depend linearly on ω^{-1} over a wide frequency range. Within this linear dispersion regime the magnitude of $J_1(\omega)$ is independent of the size of the vesicle R_0, the effective lateral tension σ and the viscosity of the surrounding medium η. It assumes the simple form

$$J_1(\omega) = \frac{k_B T}{6\kappa\omega}. \tag{3}$$

The bending elastic modulus is thus the only relevant parameter in the linear dispersion regime and can be accurately extracted from the experimental data. On the other hand, R_0, σ, η, and κ determine the frequency at which $J_1(\omega)$ levels off into a frequency independent plateau. The damping effect of the external magnetic field has been neglected so far, but it might influence the low frequency cut-off as well.

Our results show that the spin-lattice relaxation of unilamellar quasi-spherical vesicles exhibits a linear dependence on ω^{-1} in the kHz frequency range. This linear dispersion regime extends for the micrometer-sized vesicles down to 10^4 Hz, regardless of the lateral tension of the vesicle and of the water viscosity, varying in reasonable limits. An estimate shows that the contribution of the molecular lateral diffusion along the vesicle surface is at least one order of magnitude smaller than the relaxation induced by shape fluctuations. The NMR relaxometry of unilamellar vesicles opens thus a new possibility to measure the bending elastic modulus κ of membranes. This could be relevant to studies of the modulation of the membrane rigidity by different membrane constituents, such as cholesterol or proteins.

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Theoretical interpretation of the ^1H nuclear magnetic relaxation dispersion due to the relative motion of the repulsive $(CH_3)_4N^+/Gd(D_2O)_8^{3+}$ ion pair in heavy water

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Abstract

The nuclear magnetic relaxation dispersion (NMRD) of the $(CH_3)_4N^+$ proton spins is used to study simultaneously the relative translational motion of a $Gd(D_2O)_8^{3+}$ octoaqua complex with respect to a tetramethylammonium $(CH_3)_4N^+$ ion and the quantum dynamics of the Gd^{3+} electronic spin. The $(CH_3)_4N^+$ proton longitudinal relaxation rate $1/T_{1n}^e$ is interpreted in a quantitative way at the measured proton resonance frequencies, ranging between 10 and $800MHz$. A pronounced maximum of $1/T_{1n}^e$, previously found by Dinesen and Bryant [1], is observed around $90MHz$, which corresponds to an applied field $B_0 \cong 2.2T$. This behavior is interpreted [2] by assuming that the relative diffusion of $Gd(D_2O)_8^{3+}$ with respect to $(CH_3)_4N^+$ accounts for their repulsive potential of mean force, calculated with the help of the hypernetted chain approximation for two charged hard spheres in discrete, polar, and polarizable water [3-5], and by using a detailed picture of the Gd^{3+} electronic relaxation, based on an independent electronic paramagnetic resonance(EPR) study. The standard dipolar nuclear relaxation formalism of Solomon and Bloembergen, valid for the above frequencies, leads to an overall good agreement with the experimental data, without any adjustable parameter. The maximum of the NMRD profile can be explained as follows. When the applied field B_0 increases from 0.23 to $2.2T$, the rise of $1/T_{1n}^e$ is due to the simultaneous increase of the electronic longitudinal relaxation time T_{1e} [6,7]. On the other hand, when B_0 exceeds $2.2T$, the effects of the electronic relaxation on the proton relaxation rate $1/T_{1n}^e$ become negligible, so that it displays the usual decrease of the intermolecular dipolar spectral density. It is shown that for all fields, the Coulomb repulsion between the $(CH_3)_4N^+$ and $Gd(D_2O)_8^{3+}$ cations reduces the theoretical values of $1/T_{1n}^e$ by a factor of about 2 with respect to the predictions of the Ayant, Belorizky [8], Hwang, and Freed [9] (ABHF) reference model of two neutral hard spherical solutes diffusing in a viscous continuum. The short life time of the Gd^{3+} electronic levels leads to an attenuation of $1/T_{1n}^e$, which becomes significant for $B_0 \leq 3T$ and reaches a value as small as 0.5 at $B_0 = 1T$. NMRD experiments using probe solutes of well-known spatial dynamics with respect to a Gd^{3+} complex can be combined with the Solomon-Bloembergen theory to provide an indirect estimate of the longitudinal electronic relaxation time in this complex. This knowledge is useful in the theory of magnetic resonance imaging relaxivity.

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Recent Developments in Field-Cycling MRI – Free Radicals and Quadrupole Dips

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As indicated by the title of this conference, and discussed in several of the presented papers, field-cycling has found its main application in relaxometry. Nevertheless, field-cycling has also been used by a small number of groups in MR imaging, either to improve its sensitivity or to provide novel contrast mechanisms. This lecture will describe two aspects of field-cycling MRI, namely its use together with the Overhauser effect to image free radicals, and its application to the study of quadrupole dips in biological samples.

PEDRI (proton-electron double-resonance imaging, also known as Overhauser Imaging) is a method for imaging free radical distributions *in vivo*. It involves the irradiation of an EPR resonance of a free radical of interest during the collection of an NMR image [1]. In regions containing the free radical the Overhauser effect causes a transfer of polarisation from electron to nuclear spins, resulting in an enhancement of the NMR signal, which in turn reveals the distribution of the free radical in the image. PEDRI is normally implemented at low field (~10 mT) with EPR irradiation at ~250 MHz, but even under these conditions non-resonant absorption of the EPR irradiation is a significant problem, particularly in *in vivo* experiments. In field-cycled PEDRI (FC-PEDRI) the EPR irradiation is applied at lower field (2-5 mT) with correspondingly lower frequency and lower absorbed power, while the NMR signal is observed at a higher field to improve the signal-to-noise ratio (SNR) [2]. We have used FC-PEDRI to study the distribution of stable free radical contrast agents *in vivo*. FC-PEDRI can provide information on organ function and, by making use of the EPR spectral properties of these agents, to measure local pH [3] and oxygen concentration [4]. Figure 1 shows FC-PEDRI images of an anaesthetised rat following the intravenous administration of a dose of triarylmethyl (TAM) free radical. Organ structures and blood vessels are clearly visible in the image obtained with the EPR irradiation switched on.

FC-PEDRI experiments were carried out using a whole-body sized field-cycling MR imager constructed in our laboratory [5]. It uses a whole-body permanent magnet with a vertical field of 59 mT which provides the detection magnetic field. Field cycling is accomplished by the field-compensation method: a resistive, whole-body sized, saddle-shaped magnet is fitted into the bore of the permanent magnet, and the field from this secondary magnet can add to or subtract from the field of the permanent magnet. A field change of 59 mT can be achieved in 40 ms. There are no problems with eddy currents because the permanent magnet is made of ferrite, and the support structures are also non-conducting. The imager is controlled by a commercial MRI console.

It is well known that proton relaxation in proteins and other bio-polymers can be strongly affected by interactions with the quadrupolar nucleus ^{14}N, where ^{14}N–^{1}H groups act as "relaxation sinks". This gives rise to "quadrupole dips", reductions in the proton spin-lattice relaxation time which occur at the three NMR frequencies corresponding to the ^{14}N nuclear quadrupole transitions. This effect was studied extensively in the early to mid 1980s, and quadrupole dips were measured in hydrated proteins and various biological samples [6]. In the early 1990s Carlson *et al*. performed human relaxometry measurements using a small field-cycling coil inside a whole-body permanent-magnet MRI system [7]. We have implemented field-cycling inversion-recovery relaxometry and imaging pulse sequences on our whole-body field-cycling imager, and have studied quadrupole dips in human muscle *in vivo*. Inversion-recovery images obtained on and off the quadrupole dips exhibit significant differences,

giving a novel contrast mechanism. Another biological system which exhibits quadrupole dips is illustrated in Figure 2 – the boiled egg! The measurement of quadrupole dips offers the possibility of non-invasive measurement of protein concentration [8], so may be of use in the characterisation of muscle-wasting diseases.

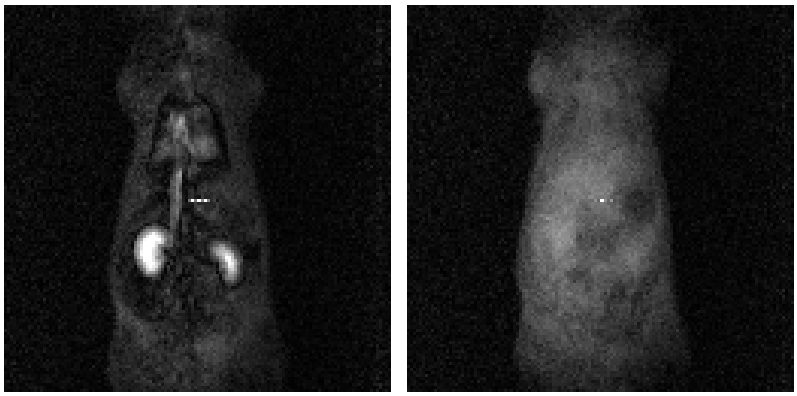

Figure 1: FC-PEDRI images of anaesthetised rat given 0.57 mmol/kg dose of TAM free radical (kindly donated by Nycomed Innovation, Malmö, Sweden). Detection field: 59 mT; Evolution field 4.25 mT. Left: image with EPR irradiation at 120.7 MHz. Right: image without EPR irradiation.

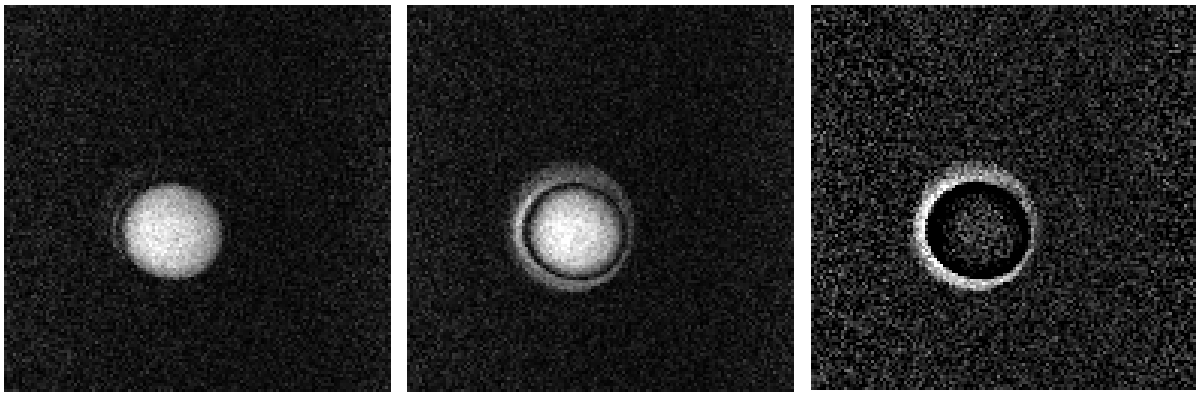

Figure 2: Field-Cycled Inversion-Recovery images of a freshly-boiled chicken egg. Detection field: 59 mT; detection frequency: 2.49 MHz. TR: 1500 ms; TI: 160 ms. Left image: evolution field 65 mT (on quadrupole dip). Middle image: evolution field 75 mT (away from quadrupole dip). Right-hand image shows difference between previous images, showing the egg white where the quadrupole dip effect is observed.

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Combined Analysis of NMR and EPR Relaxation Data of Gd(III) Chelates in Aqueous Solution

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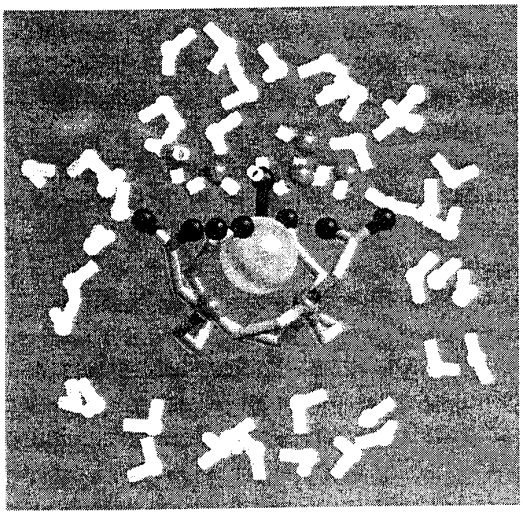
Gadolinium(III) complexes are used routinely as contrast agents in medical magnetic resonance imaging (MRI). Contrast improvement is a consequence of the enhancement of the water proton magnetic relaxation rate in tissues through interactions with the seven unpaired f electrons of the Gd(III) center. The ability of such a paramagnetic complex to accelerate proton relaxation, its relaxivity, is due to the modulation of through-space dipole-dipole interactions between the unpaired electron spin on the paramagnetic ion and the proton nuclei of the surrounding water. This effect is separated for convenience into "inner-sphere" relaxivity due to interactions with water molecules bound in the first coordination sphere of the paramagnetic metal and transferred to the bulk water by chemical exchange and "outer-sphere" relaxivity due to direct interactions with bulk water in the vicinity of the paramagnetic complex.



Inner-sphere relaxivity is governed by four characteristic time constants: the correlation time for the rotation of the complex, τ_R , the residence time of a water proton in the inner-coordination sphere, τ_m (often expressed as its inverse, the exchange rate k_{ex}) $1/\tau_m$), and the longitudinal and transverse electronic relaxation times ($T_{1,2e}$). The proton residence time under physiological conditions is normally assumed to be equal to the residence time of the oxygen nucleus since, at neutral pH, proton exchange is expected to take place primarily via the exchange of whole water molecules. The outer-sphere contribution to relaxivity depends mainly on the electronic relaxation rates and the rate at which an outer-sphere water molecule diffuses away from the gadolinium complex.

For an understanding and for a desired optimization in respect of high ^{1}H relaxivity all the parameters have to been known. As experimental methods ^{1}H and ^{17}O NMR as well as EPR, both as a function of temperature and magnetic field strength, can be used to determine the various time constants. It has been shown that a simultaneous treatment of EPR, ^{17}O NMR, and ^{1}H NMRD data leads to improved definition of the many parameters affecting the proton relaxivity of Gd^{3+} complexes.[1] This combined analysis was applied to a number of Gd(III) chelates and proved to be successful particularly to fit the NMR results.[2] The EPR experimental data, mainly linewidths of EPR resonance lines, however are often less well fitted. A magnetic field independent contribution to the relaxation had to be added, but

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nevertheless the agreement between experimental and calculated EPR linewidths was sometimes poor.

In the last two years a general theory of the electronic relaxation of an *S* state complexed paramagnetic metal ion (Mn^{2+} ,Gd^{3+}) in solution was developed.[3] It was shown that the electronic relaxation mechanisms at the origin of the EPR line shape arise from the combined effects of the modulation of the static crystal field by the random Brownian rotation of the complex and of the transient zero-field splitting. A detailed study of the static crystal field mechanism showed that, contrarily to the usual global models involving only second-order terms, the fourth and sixth order terms can play a non-negligible role. The very good agreement of experimental EPR spectra and their fitted counterparts for $[Gd(H_2O)_8]^{3+}$ and $[Gd(DOTA)(H_2O)]^-$ showed the power of the approach. Furthermore, it has been shown that the spin rotation mechanism introduced as magnetic field independent part plays a negligible role and can be omitted. The EPR line shape calculation are based on Redfield's approximation which may be inadequate in the case of complexes with long rotation correlation times and at very low magnetic fields. It is expected that Redfield's theory is valid if the following two conditions are verified: (1) $|\mathcal{H}_1|\tau_c << 1$, (2) $\omega_0 >> |\mathcal{H}_1|^2\tau_c$., where $\mathcal{H}_1$ is the time dependent perturbing Hamiltonien, τ_c the correlation time and ω_0 the resonance frequency in rad s^{-1}.

The contribution presented will for the first time show a combined analysis of ^{17}O NMR ($1/T_1$, $1/T_2$, $\Delta\omega$), ^1H NMR ($1/T_1$-NMRD) and EPR (ΔH_{pp}, g_{eff}) experimental results (measured as a function of temperature and magnetic field) using the recently developed electron spin relaxation theory. Furthermore, we are able to show that at low magnetic field the second condition for the validity of Redfield's approximation is not fulfilled. The ^1H NMRD profile of the aqua ion of Gd(III) below 0.2 T can only be fitted using a new approach,[4] which allows the calculation of relaxation rates beyond the Redfield limit. This approach is based on a Monte-Carlo numerical solution of the time-dependent Schrödinger equation for a stochastic perturbing Hamiltonian. We developed a computer program which allows a non-linear least squares fit of theoretical relaxation rates and chemical shifts to experimental data including the Monte-Carlo numerical solution mentioned above. With this program all experimental data can be fitted together using one set of parameters.

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High Field Relaxivities of Dy-complexes: the Effect of the Water Exchange Rate

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Introduction: Unlike Gd(III) complexes which enhance markedly water proton relaxation rates (R_1 and R_2), their Dy(III) analogs have very little influence on the proton relaxation rate at fields lower than 0.5 T because of the very short electronic relaxation time (τ_S) of Dy(III) as compared to Gd(III). At higher magnetic fields, however, the Curie relaxation, which depends on the magnetic field and, for small complexes, on the rotational correlation time (τ_R) significantly enhances the longitudinal relaxivity of these compounds. The theory predicts that R_2 should increase both on the magnetic field and on the exchange time (τ_M) of the water molecules coordinated to the lanthanide ion with the bulk[1,2]. In this work, various Dy complexes which are expected to exhibit small differences in τ_R but large ones with regard to τ_M are studied.

Material and Methods: ^{1}H T_1 and T_2 measurements were performed at 0.47, 4.7, 7.05, 11.75, 14.1 and 18.8 T respectively on Minispec PC-20, Minispec PC-40, Minispec MQ-60, MSL-200, Avance-200, AMX-300, AMX-500, AMX-600 and Avance 800 from Bruker. The analysis of proton relaxation rates takes into account the outersphere contribution as predicted by Gillis et al.[3] and the innersphere contribution. For longitudinal relaxation rate, both contributions result mainly from dipolar and Curie dipolar interactions. The outersphere contribution of the proton transverse relaxation rate originates also from dipolar and Curie dipolar interactions whereas the innersphere contribution results from dipolar, Curie dipolar and Curie contact interactions. The water exchange time τ_M of the Dy(III)-complex was separately obtained by the simultaneous analysis of the temperature dependence of the longitudinal and transverse relaxation rates of ^{17}O at 7.05 T (AMX-300). T_1 analysis takes into account dipolar, Curie dipolar, scalar and quadrupolar interactions. For T_2 analysis, a Curie contact term has to be added to the T_1 contributions.

Results:

The field influence on the proton longitudinal relaxivity r_1 is evident above 100 MHz (fig. 1). The values of τ_S obtained by the theoretical fitting of the data [2,3] is similar for all compounds and range between 0.12 and 0.17 ps. As expected from the rather similar size of these compounds, r_1 is equivalent for all the Dy-complexes.

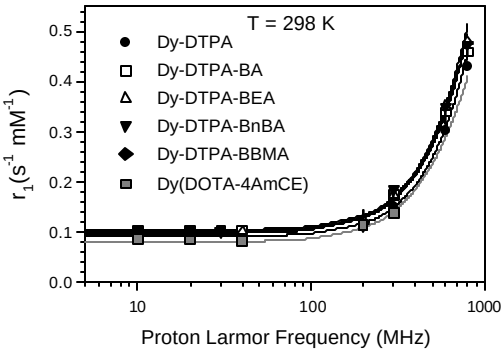

Figure 1

The field dependence of r_2 is shown on figures 2 and 3. The high field values of r_2 are significantly larger than r_1 values and markedly increased for bisamides derivatives of Dy-DTPA as compared to the parent compound. This difference is explained by the slower water exchange of the bisamide complexes as shown by the values obtained by fitting the experimental proton and oxygen-17 relaxometric data.

For the DOTA derivative, the lack of field dependence above 100 MHz and the larger relaxivities at 310 K as compared to 298 K are indicative of a slow water exchange limiting the transverse relaxivity (figure 3).

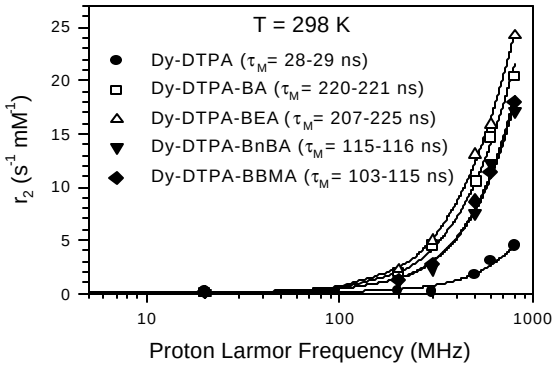

Figure 2

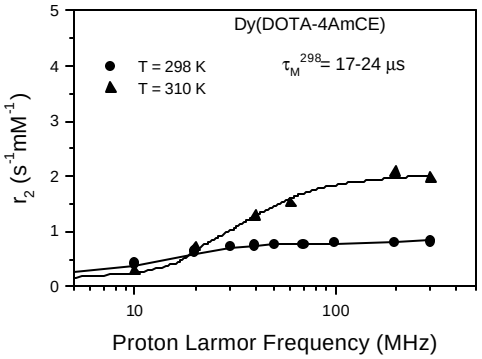

Figure3

Conclusion: This work confirms the field dependence of the longitudinal and transverse relaxivities of Dy complexes at high field. While r_1 is similar and remains small for complexes of similar molecular weight, r_2 strongly depends on the water exchange time τ_M. This work shows that, for Dy-complexes, a water residence time in the first coordination sphere larger than 1 µs restricts the transverse proton relaxivity at high magnetic field. On the other hand, a too short τ_M (τ_M < 100 ns at 298 K) limits the relaxivity at low as well as at high magnetic field. In order to reach the optimal transverse relaxivity at high magnetic fields, a τ_M value ranging between 0.1 and 1 µs is thus required. On the contrary, as shown in figure 3, at intermediate magnetic fields (0.5 to 2.4 T), slow water exchange (τ_M > 1 µs) is beneficial for the transverse proton relaxivity.

The striking evolution of r_2/r_1 ratio indicates that Dy complexes exhibiting a relatively slow water exchange might thus be of interest as "negative" contrast agents for high field imaging.

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Water Dynamics in Gd^{3+}-exchanged zeolite Y

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Zeolite Y is a synthetic faujasite with ~ 13 Å supercages connected by a network of smaller cages and channels. Gadolite, a potential contrast agent for magnetic resonance imaging of the gastrointestinal tract, is based on Gd^{3+} doped NaY. The paramagnetic gadolinium, intercalated in the zeolite cages, produces a strong contrast in the intra-zeolite and surrounding water by inducing magnetic relaxation of the water protons. The exchange of water molecules from the Gd^{3+} hydration shell to the surrounding pore water plays an important role in transmitting the paramagnetically induced relaxation effect. The ^{17}O and ^{1}H NMR signals of pore water in powdered samples are single Lorentzians typical of a liquid phase. We have performed variable temperature, multiple magnetic field ^{17}O and ^{1}H relaxation rate studies of Gd^{3+}-doped NaY with several doping ratios, and have used a Swift&Connick/Solomon-Bloembergen-Morgan approach to obtain the water exchange rate and the rotational correlation time of the intercalated aquaion. The rotation of pore water molecules is considerably hindered (slower by a factor of 20-30 at 298 K) compared to the bulk liquid. The water exchange rate at 298 K on Gd^{3+} intercalated in the zeolite supercages is within an order of magnitude of that on Gd^{3+} in solution: our results indicate that water exchange on intercalated Gd^{3+} undergoes a changeover from a normal activation energy limited regime at low temperature to a diffusion limited regime at room temperature.

Field Cycling Relaxometry: A Very Helpful Tool for Understanding the Relaxation Mechanisms of Paramagnetic MRI Contrast Agents

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Paramagnetic Gd(III)- and Mn(II)-based complexes are widely investigated as Contrast Agents for MRI protocols.[1-2] Their relaxing efficacy towards water protons is routinely evaluated "in vitro" through the measurement of the relaxivity, r_1. This parameter refers to the paramagnetic contribution to the observed longitudinal relaxation rate ($R_1=1/T_1$) of the water protons in a solution containing 1 mM of the paramagnetic agent.

Higher r_1, more efficient is the CA. Usually, three distinct components to the relaxivity may be recognized: i) a contribution arising from the exchanging water protons directly coordinated to the metal centre (inner-sphere term), ii) a contribution from the water protons diffusing around the metal complex (outer-sphere term), and iii) a contribution from the mobile protons (exchanging with the bulk water) present in the second coordination shell of the metal centre.[3]

Each contribution to the overall relaxivity results from a complex interplay of a relatively large number of structural and dynamic parameters of the metal complex, whose evaluation may be pursued through several experimental techniques. To this regard, the analysis of the magnetic field dependence of the relaxivity (NMRD technique) has a fundamental role, particularly for assessing the relative contribution of the operating relaxation mechanism to the overall r_1.

The search for more efficient CAs prompted the research groups to design metal chelates endowed with the highest possible relaxivity. This aim has been mainly pursued by developing macromolecular CAs, in which the relaxivity enhancement (mainly promoted by the inner-sphere term) is caused by the elongation of the reorientational correlation time τ_R of the water protons. Though the relaxivities of such systems are considerably higher than the corresponding small-sized complexes, the r_1 values seems to have a maximum threshold at ca. 50-60 $s^{-1}mMGd^{-1}$. This result is partly due to the non-optimal values of some key-parameters controlling the relaxivity (basically the residence lifetime of the coordinated water τ_M), but it could also arise from a faster local motion of the water protons coordinated to the metal centre with respect to the whole motion of macromolecular adduct. This hypothesis has been checked and supported by some preliminary data.

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Poster session

ULTRASOUND EFFECTS ON NEMATIC 5CB STUDIED BY FIELD-CYCLING RELAXOMETRY

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In this paper we will discuss the influence of ultrasound waves in the molecular dynamics of nematic 5CB (4-n-pentyl-cyanobiphenyl) as revealed by the Larmor frequency dispersion of the spin lattice relaxation time (T_1). Experimental and theoretical studies of nuclear magnetic relaxation in nematic liquid crystals indicate that T_1 essentially reflects two kind of molecular mechanism: collective motions called Director Order Fluctuation (ODF) and individual molecular motions, such as self-diffusion and rotations [1,2]. Collective re-orientations modes are mostly contributing to spin-lattice relaxation at low frequencies. Experimental evidences exist that contributions from ODF to the total T_1 relaxation parameter are dominant in the kHz range [3-6]. Because the aim of the work was to study the influence of a sonic perturbation in a dynamical region where ODF is a dominant mechanism, experiments were carried out using the fast field cycling technique [7-9]. The ultrasound was coupled to the sample through a 3mm-glass sonotrode matched to a 30 kHz/50W ultrasonic generator. We will present T_1 dispersion curves in a Larmor frequency band between 10 kHz and 1MHz at two different temperatures in the nematic range, in presence and absence of ultrasonic waves. Results will be discussed in terms of usual molecular dynamic theory in nematic liquid crystals.

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The two structural domains of *Azotobacter vinelandii* Rhodanese change their contact surface during the enzymatic cycle: evidence from NMRD relaxometry.

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Sulfurtransferase enzymes are widely distributed among plants, animals and bacteria. In vitro these enzymes catalyze the transfer of a sulfur atom from thiosulfate to cyanide. The Azotobacter vinelandii rhodanese (RhdA) is the only thiosulfate-cyanide sulfurtransferase identified and characterized in the nitrogen-fixing bacteria. The three dimensional structure has been recently elucidated (Bordo et al., 2000) showing a tertiary structure similar to that of bovine rhodanese. The three-dimensional structures show a single polypeptide chain arranged in two domains connected by a loop. The catalytic function of the rhodanese is located close to a cleft between the two domains; all side chains essential for the catalysis are provided by the second domain only. To investigate the structural modality of the enzymatic mechanism, a study of the interaction with hypophosphite anions has been carried out by several techniques, including nuclear magnetic relaxation dispersion (NMRD). Water proton relaxation was already measured for bovine rhodanese (Blicharska et al., 1976), indicating a tightening of the binding site cleft, interpreted as a reduction of accessibility of water.

The relaxometric profile of the native enzyme changes markedly from the ES to the E form. The marked shift of the correlation frequency toward the higher frequency region for E than for ES form is evident. This indicates that the dynamics of water molecules bound on the surface of the enzyme becomes faster upon discharging the enzyme. By fitting the experimental results by means of the model free approach (Halle et al., 1998) a difference of the rate of access of water to the surface of the macromolecule is obtained. The shape of the profile indicates that the ES form of the enzyme has a more stretched form extending to much lower frequencies than in the E form. This is in line with a different tightness (Halle et al., 1998) of the adhesion surfaces between the two structural domains of the protein. Addition of hypophosphite ion to the ES form of the enzyme produces a marked effect in the relaxometric profile. The change in level of the curve is known as a salt effect, a decrease of the frequency of the water dynamics is visible but the invariance of the stretching from one to another profile indicates that no marked change in conformation occur upon addition of anions. On the contrary, the relaxation profile of the E form indicates a slower dynamics in the presence of hypophosphite ions, becoming similar to what observed in the ES form in the absence of ions.

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RELAXOMETRIC CHARACTERIZATION OF NITRITE REDUCTASE FROM ACHROMOBACTER CYCLOCLASTES

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The nitrite reductase (NIR) from denitrifying bacteria Achromobacter cycloclastes IAM 1013 has been characterized by 1H NMRD. The profiles of AciNIR protein were collected at 298K and at 283K both in the absence and in large excess (150 mM) of azide. The titration of AciNIR protein with azide was followed by NMRD until a large excess of azide was added. The values for the hyperfine coupling constants, $A_{||}$, and for the gyromagnetic electron g factor were fixed in the fitting procedure to 0.0139 and 0.0142 cm^{-1}, and to 2.33 and 2.31, for the AciNIR and the AciNIR-azide adduct, respectively, as found from EPR measurements. The best-fit procedure for the AciNIR profile indicates the presence of four water protons at 2.9 Å from the paramagnetic center (or two water protons at 2.6 Å) and a value for the electron relaxation time of $1.2 \cdot 10^{-9}$ s. The best-fit procedure for the profile of AciNIR-azide adduct indicates the presence of two water protons at about 2.9 Å (or one at 2.6 Å) from the paramagnetic center and the same value for t_s. The relaxation rate values at 0.02 MHz versus the concentration of NaN_3 were fitted and a binding constant for azide binding was obtained, K_a = $(1.00 \pm 0.13) \cdot 10^3$ M; evidence for a second weaker binding constant could also be obtained.

Solvent ^{1}H NMRD study of hexaaquochromium(III): inferences on hydration and electron relaxation

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Information on the interactions between paramagnetic metal ion Cr(III) and water molecules has been obtained by analysing the water proton nuclear magnetic relaxation dispersions (NMRD). The profiles were collected in water and in water-glycerol solutions at several temperatures and viscosities. The data were analysed in terms of the available theories by taking into account the contributions from first sphere, second sphere and outer sphere water molecules. Dynamic parameters, like the molecular rotational time, the exchange time of the water protons of the first coordination sphere, the correlation time for electron relaxation and the magnetic field dependence of electron relaxation were obtained. The ^{1}H NMRD profiles water solutions of the chromium(III) aquaion complex are sensitive to the rotational correlation time of the complex, which is two-three times the value expected for an aquaion. In order to i) obtain a good fit and ii) reconcile t_r with a structural model, it is necessary to consider the contribution to relaxivity of second-sphere water molecules. The exchange time of the latter molecules is confirmed to be longer than the diffusional correlation time and longer than the rotational time of the complex, both being around $70 \cdot 10^{-12}$ s at room temperature. The resulting model is that of a hydrated chromium(III) ion that reorients as a rigid object carrying both first and second sphere water molecules.

AEROSIL INDUCED EFFECTS ON OCTYLCYANOBIPHENIL (8CB) ABOVE THE NEMATIC-ISOTROPIC TRANSITION AS STUDIED BY NMR RELAXATION METHODS

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Fast field cycling NMR [1,2] and standard rotating frame magnetic relaxation methods [3] were used to study the underlying molecular dynamics of confined octylcyanobiphenyl (8CB) mesogen in Aerosil [4-6]. Important differences in the information provided by the two experimental techniques will be highlighted. The role of the difference between the spherical harmonics relevant for each of the corresponding relaxation rates (T_1^{-1} and $T_{1\rho}^{-1}$) will be addressed referring to the given experimental conditions. It will briefly be demonstrated for the bulk nematic phase as a clear example. In contrast to the bulk system, a noticeable frequency dispersion of the relaxation rates was observed in the confined sample even above the bulk transition temperature. This indicates the presence of new dynamical features induced by the embedded aerosil network. Possible relaxation mechanisms will be discussed. The interpretation will be supported by computer simulations of the diffusion in the confining geometry with the orienting surface.

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NMRD relaxation measurements of $VO(PIC)_2$ system in the presence of albumin and transferrin

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The insulin-like effect of vanadium is on of the most noteworthy findings and the relationship between vanadium and diabetes mellitus has been extensively studied in the past two decades. We present the results of ^1H nuclear magnetic relaxation dispersion (NMRD) measurements in aqueous solutions of the insulin-mimetic vanadyl(IV)-bispicolinato ($VO(PIC)_2$) complex with human serum albumin and transferrin. While the NMRD profile of the water solution of $VO(PIC)_2$ has a simple shape (one inflection point) with about twofold higher magnitude of the dispersion step with respect to the NMRD profile of oxovanadium(IV) aqua solution the introduction of protein change the relaxivity significantly. This strictly indicates on the presence of the interactions between protein and vanadium complexes. The possible interpretation of our results will be presented.

Water-protein interactions in cytochromes: ^{17}O-NMR relaxation measurements

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In the frame of our studies on structure, dynamics and water interaction in the cytochrome family we have exploited oxygen-17 nuclear magnetic relaxation dispersion (^{17}O NMRD), as recently proposed by B.Halle *et al.*[1] The water-protein interactions in *horse heart cytochrome c* and *rabbit cytochrome* b_5 in both oxidation states were investigated through this technique and more detailed dynamic characterization of the long-lived water molecules has been achieved. Thus, the presence of at least three water molecules for *cytochrome c* and at least one water molecule for *cytochrome* b_5 with residence time in the range of 5ns-3μs in both oxidation states has been established. The former is in a good agreement with our previous data which had been obtained from NOE experiments [2]. The contribution of water molecules responsible for the NMRD profile in the case of *cytochrome* b_5 is lower with respect to *cytochrome c* and for both proteins shows the dependence on oxidation state. Possible explanations of our results in terms of protein mobility will be presented.

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FC-spectrometer of dynamic nuclear polarization.
Absolute zero magnetic field investigations: project and some results.

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Recently were suggested the set of equipment and method of dynamic nuclear polarization (DNP) investigation in nitroxile radical solutions in very weak magnetic fields (range 1 - 100000nT). The interest to this range of magnetic fields is caused by several reasons: investigations of fundamental features of NMR and DNP, and development of magnetometers to measure magnetic fields of the Earth and Space.

The equipment uses the method of magnetic field cycling, which is the only possible way to register NMR and DNP in the specified magnetic field range. Suggested in this work equipment has the same strategy like a previous one: processes of polarization, relaxation and measurements also are separated in time. In contrast to the earlier used equipment to work with zero magnetic fields it is supposed to apply the magnetic screen with switchable source of a homogeneous magnetic field. The general form of magnetic screen and solenoid magnetic field source is shown on the photo 1. The four layers permalloy screen are applied to achievement of magnetic vacuum of 1nT. The experiment method consists of two steps:

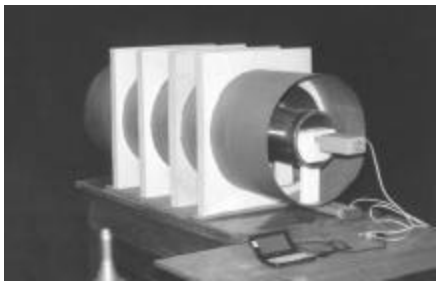

Photo 1. Laboratory magnetic screen

1. Creation of proton magnetization in a radical solution by the DNP method. To ESR saturation is applied cycle-polarized HF-magnetic field (the HF field vector rotates by left or right circle in a range of 50 -70 MHz).
2. Proton precession signal recording in magnetic field about 1Oe. A 90°-pulse or a triangular current pulse in a NMR reception coil raises signal.

The main experiment stage is the creation of proton magnetization by circular polarized HF-field. Well known that two closely spaced ESR transitions in nitroxile radicals have opposite sign of the DNP factor that results in absence of a signal in a zero field at the linear polarization of HF-fields. The HF circular pumping removes this restriction at the independent excitation of ESR transitions. The DNP amplification achieves the value of 10000 for the field of order or less than 5000nT. Unfortunately, our early experiments have not allowed to achieve weaker fields in view of geomagnetic field variations. That is the reason to apply magnetic screen.

According to the experiment results and modern DNP theory was formulated the geometric paradox. On one hand from the experimental point of view and from modern theory of DNP there are no restrictions at absolute zero magnetic field. On the other hand a circular polarization HF-field defines the plan where two perpendicular vectors are equivalent. The rights and left circle are defined only by constant field direction. There are two possible decisions in a zero fields:

1. In a zero magnetic field the sign of the proton DNP factor will form accidentally with equal probabilities depending on a spontaneous internal field which will set a direction.
2. It is most probable, that the DNP signal will decrease to zero with approaching of zero of magnetic field that will solve the specified geometrical paradox by an obvious way. The sharp reduction of DNP effect will be observed at 3 up to 30nT, which meets to NMR width. Such outcome will require development of a DNP theory taking into account a local proton field. It will give an opportunity of direct investigation of unresonant proton magnetic fields in liquids and porous media.

NMRD CURVES WITH SUB-MILLISECOND RELAXATION TIMES

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The question of how short a relaxation time can be measured with a given Field Cycling NMR relaxometer does not have a simple answer. Noack argued several years ago that, for a single-exponential process, this lower limit is essentially determined by the signal-to-noise ratio. In fact, due to field-switching times and other delays, we may observe only a small part of the decay expected in an ideal experiment. Furthermore, the observed "*amplitude of relaxation*" may be a small fraction of the maximum signal, thus leading to large uncertainties in the estimation of T_1. For given signal amplitudes and experimental conditions, we expect the statistical uncertainty of an individual measurement to rapidly increase as the relaxation time is reduced below a "critical value".

We have performed NMRD experiments with $MnCl_2$ solutions and found that the uncertainty increases by about an order of magnitude when T_1 goes from 8 ms (low field value of a 2 mM solution) to 0.25 ms (low field value of a 80 mM solution, and "practical" lower limit of our system). We have used a standard NMRD routine (40 relaxation field values from 10 kHz to 10 MHz) with pre-polarized (PP) and non-polarized (NP) sequences for relaxation fields below 4 MHz and above 4 MHz, respectively. The polarization field was 15 MHz, the observation field was 9.25 MHz, the switch times were set to 0.8 ms, and the relaxation delay was varied from 0 to four times the estimated T_1 in sixteen steps. With sixteen phase-cycled averages, the typical error is smaller than 0.3% when $T_1 > 2$ ms. At 1 ms and below, the error appears to be strongly dependent upon the relaxation field, and displays a divergent behavior with decreasing B_r below 100 kHz.

All the NMRD plots we obtained display a very smooth and "reasonable" behavior even around 4 MHz, where the acquisition sequence switches from NP to PP. While the relaxivity values at 10 MHz are essentially the same, within the uncertainty of composition, we observed a clear trend of decreasing low field relaxivity with increasing Mn^{++} concentration. The reduction observed relative to the relaxivity at 2 mM is nearly 20% in the 80 mM sample, i.e. much larger than the 2 % error of this measurement. Work is in progress to understand the field dependence of the error, the concentration dependence of relaxivity, and the possible role of artifacts occurring when measuring T_1's in sub-millisecond range.

STATISTICAL ERRORS AND REPRODUCIBILITY OF T_1 DATA IN FAST FIELD CYCLING EXPERIMENTS

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A nice feature of field cycling relaxometry is that it is largely immune to the artifacts which often affect T_1 measurements at fixed fields: partial irradiation, interference of the free induction decays of saturating and reading pulses, unwanted coherence effects in pulse trains. Under most conditions of field cycling, we expect a set of signals (fid or echoes) which change only as a function of the variable relaxation interval. Interference and coherence effects are absent, while delays associated with non-ideal field switching should contribute just constant terms and constant coefficients to the signal expression. In a first approximation, the reproducibility of T_1 data should be determined by the noise of the signals; such an *intrinsic uncertainty* is easily estimated in the non-linear T_1 fitting procedure.

In the real world, a number of non-random signal distortions may arise which cause systematic errors of T_1: they may be related with eddy currents, unstable rf and static fields, additive effects of closely spaced switching events etc. We have performed extensive tests of reproducibility collecting NMRD curves with different pulse sequences and different machines over half a year to estimate the role of these distortions. These measurements have been performed at 25°C with a 2 mM solution of $MnCl_2$ sealed in a test tube. Visually, the NMRD curves obtained with the last three systems produced by Stelar overlap very nicely, but the *F*-test applied to the sets of three data obtained at the same relaxation fields reveals that the majority of these sets has significantly ($p<0.01$) different T_1 values, i.e. values which are not compatible with the statistical errors. On the other hand, with an error of 1%, the T_1 values would have been mutually compatible. An implication is that there is no point in striving for higher quality data if the intrinsic error is below 1%.

Molecular dynamics in tilted bilayer smectic phases: a proton NMR relaxometry study

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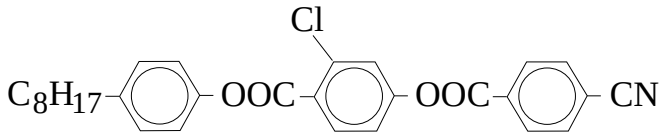
We present a comprehensive study of the NMR proton spin-lattice relaxation in the liquid crystal 4-octylphenyl 2-chloro-4-(4-cyanobenzoyloxy)benzoate, DB_8Cl for short.



$Cr - 100^{o}C - SmC_{?} - 107^{o}C - SmC_2 - 117^{o}C - SmA_2 - 155^{o}C - N - 168^{o}C - I$

This study is focused on the uniformly tilted bilayer smectic C phase (SmC_2), and on the anticlinic-like phase ($SmC_?$), which appears at lower temperature, and which is - as far its proposed structure is concerned - between the alternating and the bilayer tilted phases [1–4].

The proton spin-lattice relaxation time T_1 of DB_8Cl was measured as a function of Larmor frequency (ν), sample's orientation angle and temperature. In order to cover a broad Larmor frequency range from ~500Hz to 300 MHz, three different NMR spectrometers were used: a Bruker MSL 300 operating at 300 MHz; a Bruker SXP-4/100 for frequencies between 5 MHz and 100 MHz, and a home-built fast field-cycling spectrometer in the low frequency regime [5].

The proton spin-lattice relaxation measurements are quantitatively interpreted by a global target non-linear least-square fitting minimization procedure in which a linear combination of relaxation mechanisms' models is used: translational self-diffusion, modulating *inter*-molecular magnetic dipolar proton interactions; director fluctuations (DF), expected to be effective at low frequencies; and molecular rotations/reorientations, acting on the *intra*-molecular interactions.

Though the same relaxation mechanisms are basically present in all studied mesophases, their parameters obtained in the fit reveal the specific character of each mesophase.

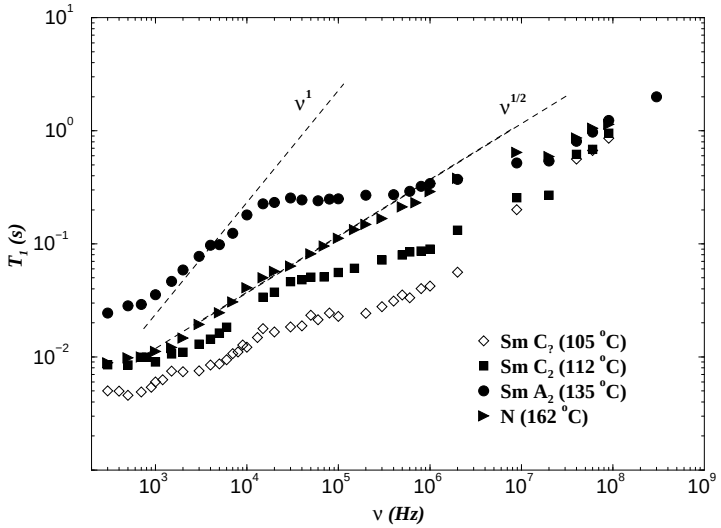


Figure 1. Frequency dependence of the proton spin-lattice relaxation time in four different liquid crystal phases of DB_8Cl.

The correlation times associated with local molecular reorientations, which are the most effective relaxation mechanism in the high frequency regime, increase smoothly with decreasing temperature as expected for a thermally activated motion. On the other hand, translational self-diffusion dominating the proton relaxation at intermediate frequencies, shows an abrupt increase in the intra-layer correlation time at the transition from the SmC_2 into $SmC_?$ phase due to the anticlinic character of the latter.

The most significant difference between the studied mesophases is observed in the kHz frequency range. In the nematic phase the usual square root dispersion profile is observed. In the SmA_2 phase a linear frequency dependence of $(T_1^{-1})_{DF}$, ascribed to the undulations of the layers, explains the experimental data. In contrast to former conjectures, we find that the T_1^{-1} low-frequency dispersion in the SmC_2 and $SmC_?$ phases can be explained only if - in addition to layer undulations - fluctuations of the director about the layer normal, which occur without distortion of the layers, are taken into account. The calculated contribution of the in-plane director fluctuations in the tilted smectic phases yields a dispersion $(T_1^{-1})_{DF} \sim \nu^{-1/2}$, similar to nematic fluctuations, which is, however, an intrinsic property of tilted smectic phases.

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IGBT PULSED SWITCHED POWER SUPPLY FOR A FIELD CYCLING SPECTROMETER

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We present some experimental results of an IGBT pulsed switched power supply for a field cycling circuit spectrometer. The power circuit combines a well-known topology with a specific control circuit using IGBT semiconductors (Fig. 1) [1]. The fast current transient responses and the steady-state current characteristic of this circuit, obtained with an FFC NMR magnet, are shown and discussed.

The implemented control circuit considers two different paths to generate the gate signals of each power semiconductor and adjust the current ripple. The protection circuits adapted with different parameters for each IGBT eliminate the over-voltages and over-currents in each circuit.

A FC magnet with ohmic resistance of 6 Ohm and self-inductance of 38 mH was used to test this circuit [2], using a maximum nominal current amplitude of 20 A (corresponding to a magnetic field of ~ 0.2 T).

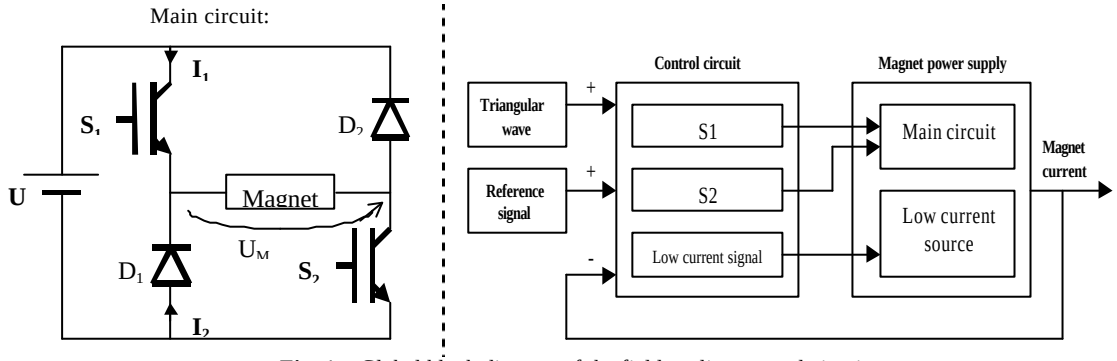

Fig. 1 – Global block diagram of the field cycling control circuit

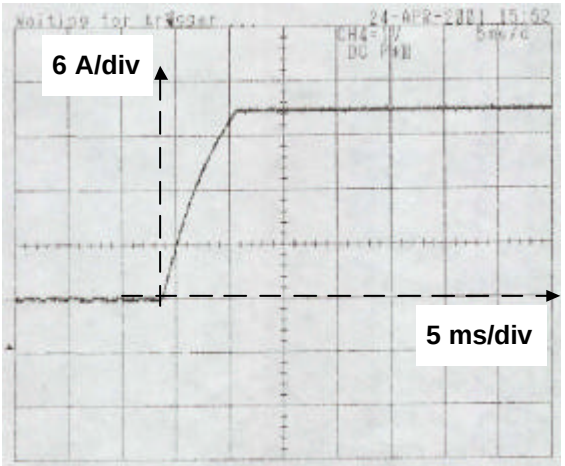

Fig. 2 - Current transient from 0 A to the nominal magnet current amplitude

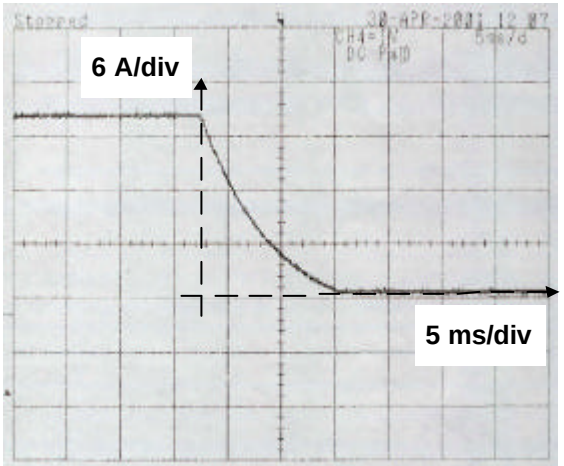

Fig. 3 – Current transient from the nominal magnet current amplitude to 0 A

The magnet current transients between the minimum and maximum values are shown in Fig. 2 and Fig. 3. In these figures, it is possible to see that the proposed power circuit assures the appropriate dynamic behavior of the magnet current.

The magnet current ripple is an important parameter to guarantee the flux density stability. The solution proposed to reduce the current ripple to be the minimum possible considers a triangular wave adjusted in amplitude and frequency which is added to the reference signal. In this way the natural ripple shown in Fig. 4 (which has a triangular waveform) is very much reduced as shown in Fig. 5.

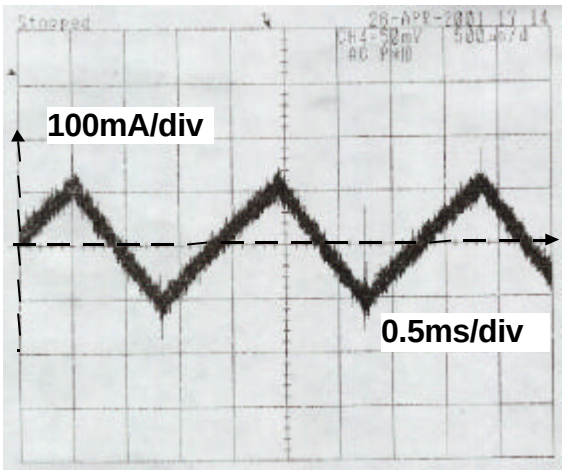

Fig. 4 - Current ripple without the triangular wave

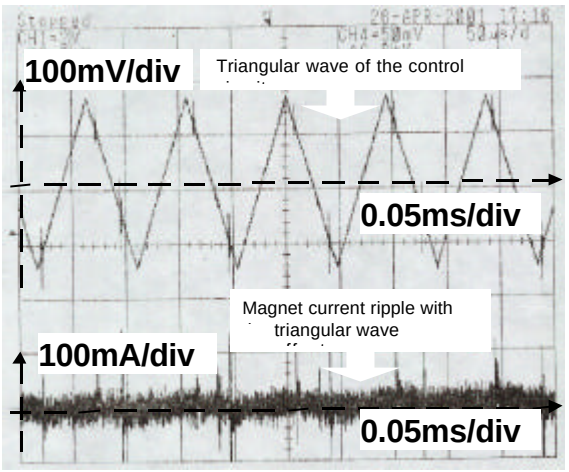

Fig. 5 – Control circuit triangular wave and the resulting magnet current ripple

The improvement of the proposed solution is discussed in terms of a reduction of the current ripple, and of the $B_{high-low}$ and $B_{low-high}$ commutation times by using semiconductors with higher commutation frequencies and addition of auxiliary circuits.

As a final remark we would like to point out that in order to improve the dynamic and steady state performances of this power supply, the use of semiconductors with high current and voltage capabilities, and high commutation frequencies are mandatory. Field cycling power supplies can be implemented with the proposed topology to drive high current magnets.

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