SIMULATION OF LONGITUDINAL AND TRANSVERSE RELAXATION INDUCED BY SUPERPARAMAGNETIC PARTICLES

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Magnetic Resonance Imaging (MRI) is based on the Nuclear Magnetic Resonance (NMR) phenomenon: after being excited by a radiofrequency field under a static field, the proton magnetic moment of a sample returns to equilibrium with two characteristic times T_1 and T_2. These times influence the MR image contrast and can be modified by magnetic particles called contrast agent. In this work, a new methodology is introduced to simulate the MR signal induced by a colloidal solution of superparamagnetic (SPM) particles used as contrast agent [1], allowing the calculation of T_1 and T_2.

1. Simulation methodology

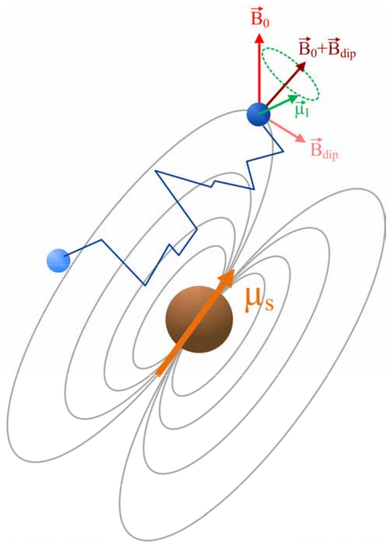

Fig. 1: Proton relaxation is due to magnetic inhomogeneities induced by a superparamagnetic particle

MR relaxation occurs thanks to the interaction between the protons and the magnetic inhomogeneities induced by the magnetic particles. The theories are usually based on the quantum formalism, **but in the case of relaxation induced by superparamagnetic particles, a classical approach can be used** [2]. Each proton i has a magnetic moment $\vec{\mu}_{Ii}$ that is perpendicular or opposed to $\vec{B}_0$ at the beginning of the sequence depending on the initial radiofrequency pulse. Each magnetic moment rotates at its own local Larmor frequency around the local magnetic field composed of the static field $\vec{B}_0$ and the dipolar magnetic field produced by the SPM particles $\vec{B}_{dip}$ (figure 1). **The dynamic of $\vec{\mu}_{Ii}$ can be described by the classical equation**

$$\frac{d\vec{\mu}_{Ii}}{dt} = \gamma_I \vec{\mu}_{Ii} \times \left[\vec{B}_0 + \vec{B}_{dip}\left(\vec{r}_i(t), t\right) \right]$$

where $\vec{r}_i(t)$ is the proton position at time t. This position is time-dependent because of the proton diffusion in the sample which can be modeled by a random walk (the SPM particle is supposed to be impenetrable).

The macroscopic magnetic moment is then obtained by averaging the different proton magnetic moments

$$\vec{M}(t) = \sum_i \vec{\mu}_{Ii}(t)$$

The signal is characterized by a mono or bi-exponential decay and fitted to obtain the relaxation times. **The main advantage of this methodology is to obtain Nuclear Magnetic Relaxation Dispersion (NMRD) of particles that are restricted by the Redfield condition (low radius or/and magnetization).**

2. Results for the isotropic model

A modeling of the effect of B_0 on the SPM magnetic moment is necessary to run the simulations. However for this preliminary work, **we supposed the magnetic moment to be isotropic and independent of B_0** (Isotropic Model). This is an unrealistic model but it provides interesting and fundamental behavior of the relaxation rates outside the Redfield condition. A magnetization of 100 Am²/kg[Fe]) was used for the simulations.

The simulation was first applied for particles with a low radius R (5 nm) and that obey the Redfield condition (figure 2). **The simulated points fit well the NMRD predicted by the Outer-Sphere theory** [3] and validate the methodology that we introduced.

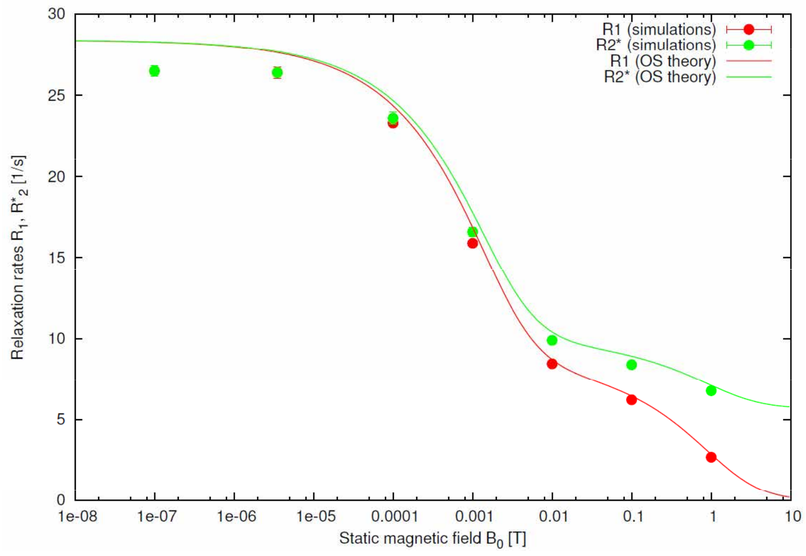

Fig. 2: Simulated and theoretical NMRDs of 5nm particles

Parameters used:
$D = 3 \cdot 10^{-9}$ m/s²; volume fraction = $3.14 \cdot 10^{-6}$

Beyond the Redfield condition (iron oxide particles larger than 10 nm), **the simulations show that the NMRDs are qualitatively similar**. Figure 3 shows the results for 230 nm nanoparticles. The profiles have some common characteristics with the Outer-Sphere model: the transversal and longitudinal relaxation rates are equal at low static fields, two inflection points appear and R_1 goes to zero while R_2 saturates at high fields. However **the magnitude of the relaxation rates are far lower than the predictions of the Outer-Sphere theory.**

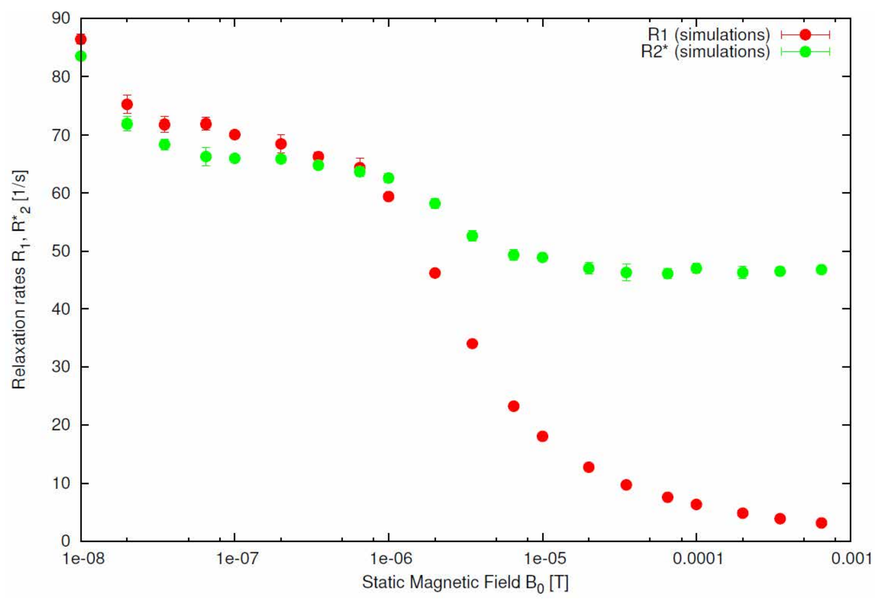

Fig. 3 : Simulated and theoretical NMRDs of 230nm particles

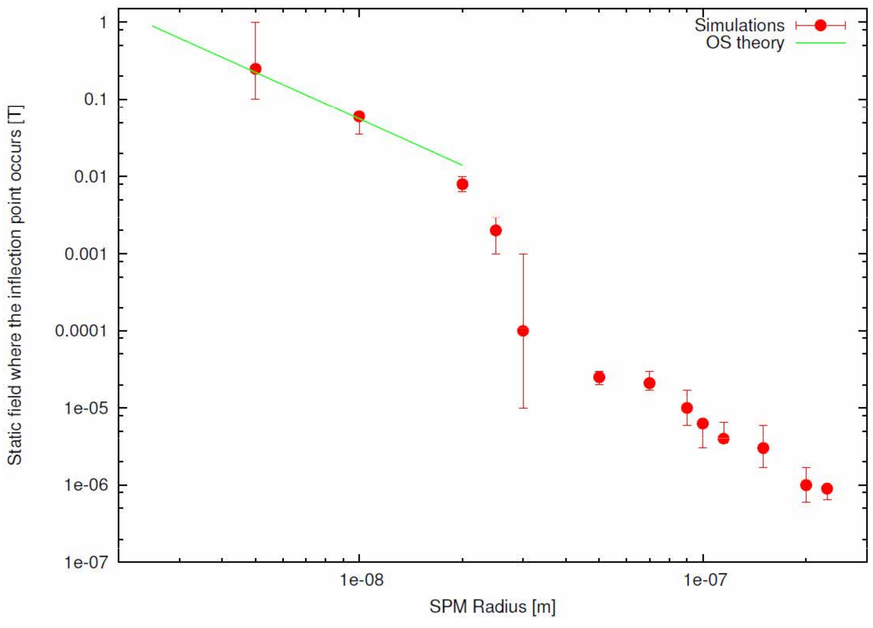

Fig. 4: Dependence of the SPM radius on position of the second inflection point.

It is well known that the inflection points provide precious information on the dynamic of the system [4]. In the outer-sphere theory, the second inflection point is given by the relation

$$\gamma_I B_0 \tau_D \approx 1$$

where $\tau_D = R^2/D$ is the translational correlation time. Figure 4 shows how the position of the second inflection vary with nanoparticle radius. **Two regimes can be distinguished**: the well known motional averaging regime of Outer-Sphere theory and a second regime that can probably be associated to the static dephasing regime, generalizing the theoretical observations for R_2 at high field [5].

Further investigations should help to understand this second regime and to simulate more realistic systems.

[1] Y. Gossuin, P. Gillis, A. Hocq, Q.L. Vuong, A. Roch, *MR relaxation properties of superparamagnetic iron oxide particles*, WIREs Nanomed Nanobiotechnol 1, 299-310, 2009.
[2] H.E. Rorschach, A classical Theory of NMR Relaxation Processes, J. Magn. Reson. 67, 519-530, 1986.
[3] A. Roch, R.N. Muller, P. Gillis, *Theory of proton relaxation induced by superparamagnetic particles,* Journal of Chemical Physics 110, 11, 5403-5411, 1998.
[4] B. Halle, J. Haukur, V/ Kandalai, Model-Free Analysis of Streched Relaxation Dispersions, J. Magn. Reson. 135, 1-13, 1998.
[5] P. Gillis, F. Moiny, R.A. Brooks, *On T2-Shortening by strongly magnetized spheres: a partial refocusing model,* Magn Reson Med, 47, 257-263, 2002.