Fast ρ-NQR Imaging with Slice Selection*

H. Robert and D. J. Pusiol

Facultad de Matemática, Astronomía y Física, Universidad Nacional de Córdoba, Ciudad Universitaria - 5000 Córdoba, Argentina

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A combination of a new pulse sequence allowing fast data acquisition in the rotating frame version of NQR (ρ-NQRI) together with a method for slice selection, is reported. The procedure allows us to record the magnetization evolution during its motion in the rotating frame. At the same time a zero-crossing external magnetic field gradient is applied in order to select a determined slice of the object to be imaged. The experiments reported are the first steps toward a fast tridimensional ρ-NQRI; even more, as the spectroscopic information is preserved during the spatial encoding procedure, it could be considered as a 3D spatially resolved NQR spectroscopy technique.

1. Introduction

Nuclear Quadrupole Resonance Imaging in the rotating frame (ρ-NQRI) [1] is based in the idea proposed by Hoult [2] for the NMR homologue case. The spatial information is encoded through the nutation frequency ω_1; i. e. in practice by means of a linear gradient of the radiofrequency (rf) field, H_1. A one-dimensional spin density profile is reconstructed from a 2D data matrix $S(t, t_1)$, which is in turn created by recording the free induction decay (FID) signal as a function of the evolution time t and incrementing the rf pulse length t_1 parametrically from experiment to experiment. After that, $S(t, t_1)$ is converted to the frequency domain $S(\omega, \omega_1)$ by means of a 2D evaluation procedure of the FIDs: a Fourier transform over t and a deconvolution procedure (for instance, using the Maximum Entropy Method [3]) along the pseudo-time domain t_1. ρ-NQRI is in fact a positional spectroscopy technique (x-NQRS) [4]; i. e. a spatially resolved spectrum $S(\omega,\ \omega_1(x))$ gives the NQR spectrum at the coordinate x.

The above procedure, hereafter referred to as the multi-experiment imaging (MEXI), consumes a long acquisition time. For example for a fixed resonance frequency ω_o, the conventional signal intensity for a complete set of t_1 increments – the pseudo-FID signal – must be measured and the time required for this is essentially the recycle delay between transients (T_r) times the number of increments in t_1 (in the practice T_r are seconds). Typically, the data acquisition time necessary to reconstruct a single profile (one-dimensional image), from a 10 times averaged 64 data points pseudo-FID, takes about 12 minutes.

Basically the reduction in the acquisition time is achieved by recording the evolution of the whole magnetization in a single scan during its motion in the rotating frame [5]. The object is irradiated by a burst of short, intense and coherent rf pulses (typically, 10 µs width) and separated by short acquisition intervals τ (about 30 µs). As the pulses are coherent, the flip angles α accumulate. The pseudo-FID is directly constructed with the amplitude of the FIDs recorded during the time following each rf pulse. Thus, a single experiment imaging (SEXI) procedure allows to image a profile leading to a considerable reduction, one or even two orders of magnitude, in the data acquisition time.

For imaging a determined slice of the object, a zero crossing static magnetic field gradient ($\nabla\mathbf{B}$) was applied to the sample while the above described imaging procedure was running. The NQR line arising from the plane experiencing the external $\mathbf{B} = 0$ is not affected [6], while for the regions of the object away from the *zero field plane* the resonance spectrum is inhomogeneously broadened. Therefore the strongly Zeeman perturbed regions of the sample give a weak contribution to the on-resonance position of the spectrum. By irradiating at the frequency corresponding to the NQR spectrum non-perturbed by the Zeeman

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Reprint requests to Dr. D. J. Pusiol.

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field, a sensitive slice around the zero magnetic field plane is defined.

The quantum mechanical calculations, showing that the pseudo-FID acquired by using the SEXI pulse sequence is equivalent to that constructed from the set of pure NQR spectra provided by the MEXI procedure, are briefly described in the next section.

2. Theoretical considerations

2.1. MEXI and SEXI equivalencies

The effect of the pulse sequence on the nuclear magnetization evolution in the NMR case can be visualized as a series of $\mathbf{I}_z$ rotations through the precession angle $\omega_o\tau$, followed by the $\mathbf{I}_y$ rotation through the nutation angle α $(\omega_1 t_1)$. Only for on-resonance spin or those with resonance offsets which evolve by $2\pi k$ (where k is an integer) during τ, there is no effective rotation and the nutation angles α accumulate [7, 8].

Unfortunately, in pure NQR there is no such pictorial description, thus a quantum mechanical treatment of the spin dynamics shall follow.

In a spin $I = 3/2$ polycrystalline quadrupole system, the nutation signal (or pseudo-FID) obtained by the MEXI experiment (i. e. rf pulses of variable length t_1 and producing a gradient of H_1 in the x-direction), is given by [9]

$$F(t_1) \sim \int_0^{+\infty} \mathrm{d}x\, \rho(x)\, H_1(x) \cdot \int_0^{2\pi} d\phi \int_0^{\pi} d\theta\, \sin\theta\, \lambda\, \sin(\omega_1'\, t_1), \tag{1}$$

where we have defined λ by

$$\lambda = \frac{1}{2a\sqrt{3}} \left((2\eta\cos\theta)^2 + \sin^2\theta(9 + \eta^2 + 6\eta\cos 2\phi)\right)^{1/2} \tag{2}$$

and the effective nutation frequency by

$$\omega_1' = \lambda\gamma H_1\,; \tag{3}$$

the coefficient a is defined by $a = \sqrt{1 + \frac{\eta^2}{3}}$, where η is the assymmetry parameter of the electric field gradient (EFG) tensor at the quadrupole nucleus. The polar and azimutal angles θ and ϕ define the relative orientations of the principal axes of the EFG tensor and the H_1 field direction; finally γ is the gyromagnetic ratio.

The calculation of the quadrupole spin-system response to the burst of rf pulses has been carried in [5] by using the formalism developed by Pratt [10]. The so called $\mathcal{L}$, $\mathcal{A}'$, and $\mathcal{B}'$ operators provide a simple and convenient *basis set* to describe the effects of rf pulses on the spin-density operator. Using this formalism, it has been demonstrated that the resulting expression for the SEXI pseudo-FID is exactly the same as $F(t_1)$ given in (1).

2.2. Selectivity of the external magnetic field

The Zeeman field gradient was produced by a Helmholtz coil arrangement consisting of two coils of radius 30mm and separated by a distance of 60mm, and carrying the current in opposite sense. Figure 1 depicts the calculated magnitude of the magnetic field produced by the anti-Helmholtz coils system in the spatial region occupied by the object in our experiment. Different currents have been assumed to circulate through de coils, shifting the zero-field plane to the right. Chlorine-35 spectra of paradichlorobenzene showing the effect of the static Zeeman field gradient

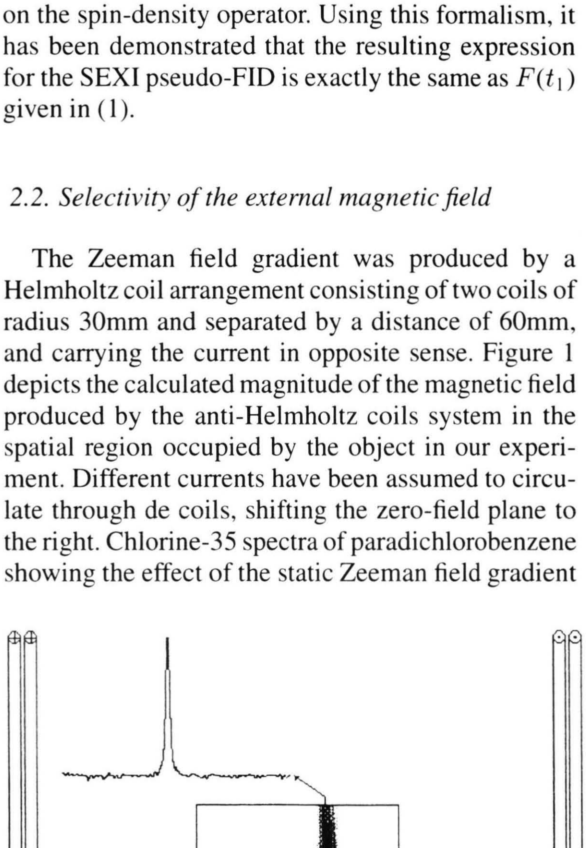

Fig. 1. Shape of the selective slice for the anti-Helmholtz coils pair used in this work. The thickness of the selective slice is about 3mm. See text for details.

are included in the figure. The upper one corresponds to the pure NQR spectrum and was assigned to the zero-field plane (the intense blacked area in the figure). The lower spectrum has been strongly frequency dispersed by a magnetic field of about 15 G, being assigned to a plane separated by approximately 1.5 mm from the zero magnetic field one. In practical terms, the magnetic field gradient defines an approximately 3 mm thick slice within which the NQR signal can be detected. Every signal outside the slice is virtually destroyed. The thickness of the selective slice can be improved by increasing and/or by shaping the magnetic field gradient.

3. Experimental

The apparatus is a homemade pulsed broadband fully computer controlled NQR spectrometer, now equipped with a Kalmus LP1000 rf power amplifier. It was basically described in [3, 5, 6]. A pulse programmer was designed for this application. It was implemented as a card inserted in one of the slots of the spectrometer dedicated AT 486 DX2 computer, and it has eight TTL pulsed outputs and other three train composite outputs. The 10 MHz clock from the rf synthesizer PTS 310 is used to synchronize all the spectrometer functions. The software for the whole spectrometer control and image reconstruction was developed in our Laboratory. The program for data evaluation was provided by Prof. R. Kimmich (University of Ulm, Germany).

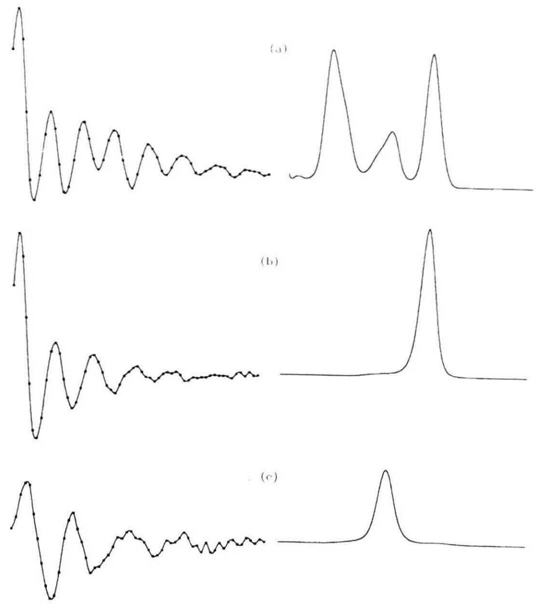

Fig. 3. a) Pseudo-FID and profile along the cylindrical symmetry axis of the object imaged without external magnetic field. The three peaks represent the respective projection of the NQR active cylinders. b) the same as a) but with the magnetic gradient selecting the right hand cylinder. c) nutation signal and profile measured after shifting the **B** = 0 plane towards the central cylinder.

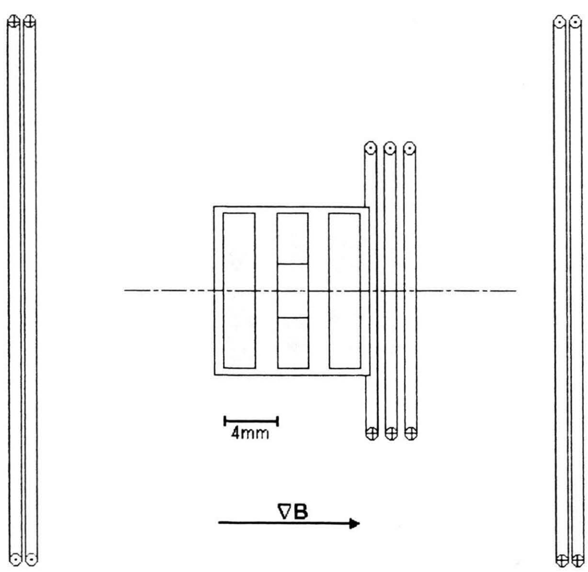

Fig. 2. Schematic arrangement of the surface rf and the selective magnetic gradient coils, together with the cross section of the object used for the test experiment. The selective static field gradient (∇**B**) is applied in a direction normal to the desired image plane.

The object used for testing the procedures consists in three parallel cylindrical layers of paradichlorobenzene, each of 12 mm in diameter and 2.5 mm thick. Two 1.5 mm thick PTFE spacers were located between the NQR active material. The cylinder located in the middle of the object has a central circular hole of 4 mm in diameter (see Figure 2).

In order to see how the slice selective and SEXI technique work together, we have arranged the rf and magnetic field coils in parallel. In this way, depending on the localization of the **B** = 0 plane, only one of the cylinders can be selected. By changing the current ratio between the coils, the sensitive plane was scanned through the object. The burst of pulses for the SEXI technique was composed of 64 rf pulses of 10 μs width and separated by 30 μs. The acquisition time with the new fast method was about 10 seconds with 10 transients per pseudo-FID. Figure (3a) shows the pseudo-FID acquired by the SEXI method in the condition of $\mathbf{B} = 0$ in the sample region. The MEM reconstructed profile is shown in the same figure and reveals the three peaks corresponding to the projection of the layers in the rf field gradient direction. Note the smaller intensity of the central peak with respect to the others, in agreement with the small quantity of NQR active material of the central cylinder due to the internal hole. Figures 3(b) and 3(c) show the effective selection of the first cylinder (closer to the surface coil) and the selection of the cylinder located in the middle of the whole object. The profiles were corrected for the distance dependence of the detection sensitivity and for the nonlinearity of the rf amplitude. As can be clearly seen in the figures, the signal arising from the unselected region is destroyed by the action of the external magnetic field.

4. Conclusions

Whiting the conditions of our experiment, at least two order of magnitude in the data acquisition time are saved by using the SEXI technique. Depending on the signal to noise ratio of the NQR signal and the desired quality of the image, parameters which determine the number of signal averaging, the acquisition time could be reduced from several minutes to a few seconds.

By combining the slice selection technique with the conventional 2D-ρNQRI, a depth resolved selected plane can be obtained to build-up a two - or even three - dimensional NQR Image.

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