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MAS as a Tool for Suppressing Dipolar Field Effects in High-Resolution Liquid NMR

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We propose high-resolution magic angle spinning as a radical method for the suppression of dipolar field effects in liquid NMR. This technique works for any sample shape and any spatial distribution of nuclear magnetization. Furthermore, it removes any possibility of spectral clustering or instability due to the dipolar field.

INTRODUCTION

NMR in solution is very often used to study the structure and dynamics of diluted molecules. When the experiments affect nuclei which are present in the sample at high concentrations (e.g., protons in H_2O), these nuclei cause large collective effects which generate undesired (*1*) additional spectral features and can even make "simple" experiments impossible.

Radiation damping is the collective effect in which the precessing spin magnetization induces an RF emf in the sample coil, which generates an RF current, hence an RF magnetic field which acts back on the spins and tends to rotate the spin magnetization back toward its equilibrium direction. The rate of this rotation is proportional to the total spin magnetic moment, the Q of the coil, and the filling factor. In a typical liquid NMR spectrometer, with a large sample of water initially in equilibrium, this rate can be up to many hundred radians per second, hence much larger than many of the spectral features of direct interest. Of course, one can use a very small filling factor if the correspondingly small sensitivity is acceptable. Various electronic techniques have been proposed and demonstrated for the control of RF current in the coil (*2–4*), hence of radiation damping, but, up to now, the manufacturers have shown little enthusiasm in providing high-quality versions of the required hardware. The standard solution to the problem is to use field gradients (usually pulsed) which "suppress" the total precessing magnetization most of the time. This, however, places additional constraints on the sequence of pulsed field gradients and leaves open the problems of interplay of radiation damping with selective pulses.

The other collective effect is caused by the nonzero average dipolar coupling of each spin with all other spins in the sample. This can be described as an additional classical field, called dipolar field (also called "demagnetizing field" or "distant dipole field"), acting on each spin (*5*). In liquids, the dipolar coupling with close-by neighbors is averaged out to zero by the fast Brownian motion, leaving only the influence of distant spins. Due to the long range of the dipolar interaction, the resulting dipolar field is, in general, not zero, and depends upon the position, the overall distribution of spin magnetization, and the shape of the sample. The dipolar field $\mathbf{B}_{\text{dip}}(\mathbf{r}, t)$ at position $\mathbf{r}$ is linearly related to the spin magnetization (i.e., the average magnetic moment per unit volume) $\mathbf{M}(\mathbf{r}', t)$ at all other positions $\mathbf{r}'$ in the sample. The typical dipolar field due to the protons of water in equilibrium at 14 T shifts the NMR frequency of the protons by about 1 Hz. Such a small shift would be completely innocuous if it were time independent; however, whenever the magnetization is tipped by pulses or interactions, the dipolar field is also tipped accordingly, hence causing complicated time dependences of the NMR frequencies in multiple-pulse experiments and the appearance of a wealth of stray peaks after Fourier transforms. In most experiments, this makes it very desirable to suppress dipolar field effects.

The standard properties of the dipolar field indicate a number of idealized situations in which a nonzero magnetization generates a zero (or innocuous) dipolar field. A uniform magnetization in a sample of ellipsoidal shape generates a dipolar field which is also uniform inside the sample. For a spherical sample, this dipolar field is exactly zero. For samples in the shapes of a (very long) cylinder or a (very wide) plane slab, the secular part of the dipolar field (i.e., the relevant part for spin dynamics) has a $(1 - 3\cos^2\theta)$ dependence upon the angle θ between the axis of symmetry and the direction of the large external field $\mathbf{B}_0$, hence it goes through zero at the "magic angle" $\theta_{\text{magic}} = \cos^{-1}(\sqrt{\frac{1}{3}})$. This last prediction is confirmed by experimental results, which we report here, obtained on a sample contained in a long, thin capillary tube. It should be noted that this mechanism does not operate efficiently for the more compact samples used in standard MAS experiments.

Another type of simple situation, which arises almost inevitably in experiments involving field gradients, is that of a magnetization depending upon position as a stationary plane wave with a wavelength much smaller than the size of the

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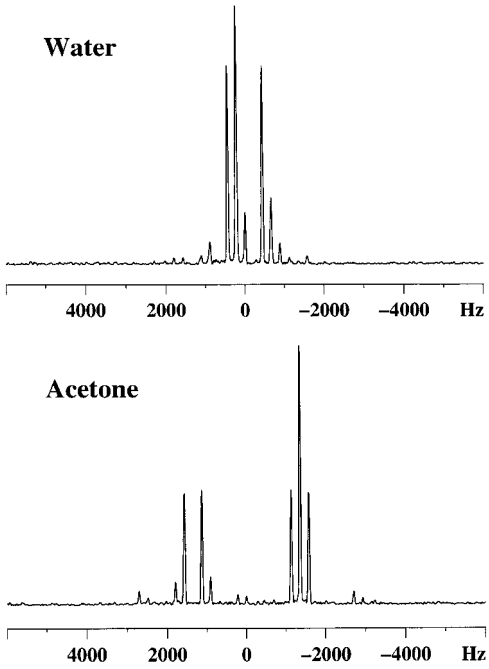

FIG. 1. The sample is a mixture of 90% water and 10% acetone in a capillary tube parallel to the external magnetic field. The offset is 220 Hz for water and −1350 Hz for acetone. The skyline projections correspond to the regions of the absolute value COSY spectrum centered on the acquisition offsets ω_2 for H_2O (top) and acetone (bottom). The horizontal offset scale is the indirectly detected frequency ω_1. The vertical scale is larger for acetone to improve the visibility of the peaks. The strong, unusual satellites of the diagonal peaks are due to dipolar field effects.

sample. In this situation, the plane wave modulated part of the dipolar field at position **r** can be expressed in terms of the plane wave modulated part of the magnetization at the same position **r**, except for a thin layer (of the order of magnitude of the wavelength) at the surface of the sample. The modulated part of the dipolar field has a secular part of exactly zero if the perpendicular to the plane is tilted at the magic angle (*8*). However, one should not forget that the "unmodulated" part of the magnetization still generates its own component of the dipolar field, which depends directly upon the overall shape of the sample (*9*). The methods mentioned above, for the suppression of the spectroscopic effects of the dipolar field, depend upon a precise balance between contributions to the dipolar field arising from different parts of the sample.

An alternative technique has been proposed and demonstrated for the elimination of undesired dipolar field effects caused by the solvent spins in homogeneous situations, which consists of a decoupling of these spins by weak selective irradiation, for instance, by the DANTE method (*10*).

Besides their obvious limitations and interferences with other aspects of multiple-pulse experiments, all of the methods mentioned above assume that the "large" magnetization, which could cause unwanted dipolar field effects, is *exactly* uniform or has some *exactly specified* spatial dependence. Obviously, this assumption can only be a first approximation in any real experiment. Making things worse, one of us has indicated recently that, in the typical dynamical situation after a large pulse, magnetization inhomogeneities tend to grow rapidly under the effect of the dipolar field inhomogeneities which they create (*11*). This mechanism of instability is not suppressed by using a spherical sample (*11*) and, presumably, is also not suppressed by the static magic angle techniques mentioned above, hence a more radical scheme is highly desirable for the elimination of dipolar field effects in high-resolution NMR.

The radical scheme which we propose here is to spin the liquid sample at the magic angle, using the recently developed high-resolution MAS probes (or slow rotation versions thereof). As usual, this rotation does not interfere with the use of pulsed field gradients applied parallel to the rotation axis. At a high enough spinning rate, MAS will average out to zero the secular part of the dipolar field seen by any nucleus in the sample caused by the magnetization in each separate volume element in the sample, irrespective of the shape of the sample and of the spatial distribution of the magnetization. In a liquid, the large dipolar interactions at very short distance are very efficiently averaged out by the fast molecular Brownian motion. The residual dipolar interactions which have to be averaged out by the rotation are just the coupling with the dipolar field, typically about 1 Hz, so that extremely modest spinning rates are sufficient.

A complete experimental demonstration of this property on a realistic large sample (i.e., a full MAS rotor) was not possible because we still lack a high-quality setup for the electronic suppression of radiation damping. In the mean time, we present

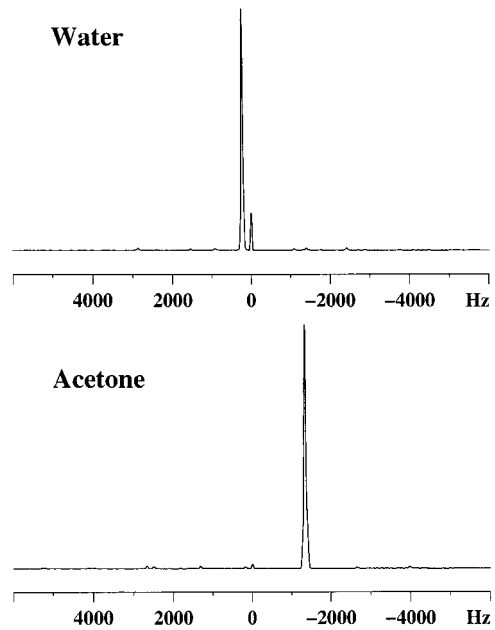

FIG. 2. The same experiment as in Fig. 1, with the capillary tube at the magic angle with respect to the external magnetic field, without rotation. The satellite peaks due to dipolar field effects have vanished, as expected.

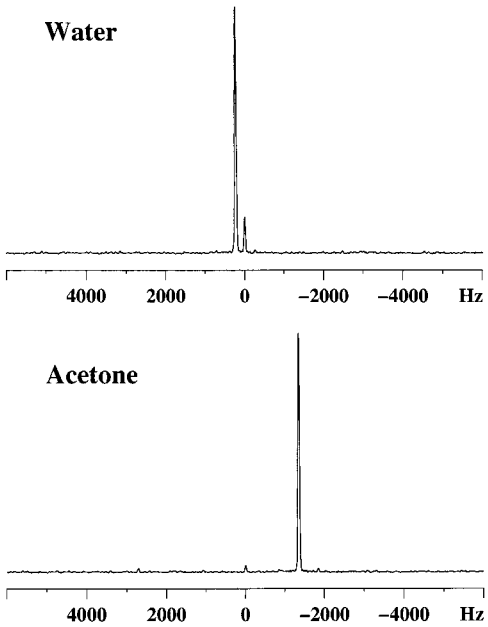

FIG. 3. The same experiment as in Fig. 2, with rotation of the capillary sample at the magic angle at about 500 Hz. The results are essentially the same as without rotation, again as expected.

experimental results on a small sample, contained in a long, thin glass capillary tube, which indicate that such a rotation (at the "slow" limit of our MAS probe, about 500 Hz) does not cause any visible spurious features in a simple COSY spectrum.

EXPERIMENTAL

The experimental conditions used here are very similar to those of Ref. (*10*), and the spectra were also obtained with the 600-MHz Bruker AVANCE DMX spectrometer at the Institut Pasteur de Lille. The samples consisted of a mixture of water and acetone in 10/1 proportions by volume, with addition of about 10^{-3} M $CuSO_4$ to shorten the proton T_1 down to 1.04 s for water and 3.4 s for acetone. A relaxation delay of 10 s was introduced between successive experiments. Radiation damping effects were made negligible by using samples of very small volume contained in thin glass capillary tubes. A total of 1024 increments and standard squared sinus apodisation were used in each dimension of the COSY experiments.

The first experiment is essentially a repetition of our previous results (*10*). The capillary sample was parallel to the large external field $\mathbf{B}_0$ and surrounded by a 5-mm tube containing the D_2O used for the lock. As indicated in Fig. 1, the results show the numerous strong additional peaks due to the dipolar field, as expected.

The following experiments were performed with a capillary sample centered in the empty 4-mm rotor of a HR-MAS probe. No lock was used. Figure 2 shows the results obtained without rotation (capillary sample at the magic angle). The additional peaks due to the dipolar field are not visible any more, again as expected. Figure 3 corresponds to the same situation, but with rotation at about 500 Hz. Compared to Fig. 2, very weak rotation sidebands appear, which are presumably due to vibrations of the rotor or other imperfections.

CONCLUSION

We have proposed the use of magic angle spinning as a radical scheme for the complete elimination of all dipolar field effects (additional peaks, multiple echoes, spectral clustering, instabilities, . . .) in high-resolution liquid NMR. Experimental results obtained on capillary tubes indicate that this scheme will work on spinning samples of any size and shape. However, the full benefit of this new method will often be difficult to achieve due to the present lack of a suitable technique offered by manufacturers for the suppression of radiation damping.

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