25 June 1999

ELSEVIER

Chemical Physics Letters 307 (1999) 41–47

CHEMICAL PHYSICS LETTERS

Sensitivity enhancement of the MQMAS NMR experiment by fast amplitude modulation of the pulses

P.K. Madhu [a], Amir Goldbourt [a], Lucio Frydman [b], Shimon Vega [a,*]

[a] *Department of Chemical Physics, Weizmann Institute of Science, Rehovot 76100, Israel*
[b] *Department of Chemistry (M/C 111), University of Illinois at Chicago, 845 W. Taylor Street, Chicago, IL 60607-7061, USA*

Received 11 January 1999; in final form 13 April 1999

Abstract

We report here an improved way of doing the multiple-quantum magic-angle spinning (MQMAS) NMR experiment that relies on the use of amplitude modulated pulses. These pulses were found to yield MQMAS NMR signals that are considerably stronger ($\approx$ 200–300%) than the ones arising from the usual continuous wave pulse schemes by virtue of a superior efficiency of the triple- to single-quantum conversion process. Numerical simulations and experimental results taking ^{23}Na and ^{87}Rb nuclei as examples are presented that corroborate the usefulness of this approach.

1. Introduction

A majority of elements in the Periodic Table are quadrupolar in nature, having their most abundant isotope with a spin greater than 1/2. The study of these species in the solid state has found important applications in many fields including inorganic chemistry, catalysis and geochemistry. One of the main challenges faced by solid state NMR spectroscopy has been the acquisition of high resolution spectra from such nuclei that shall be devoid of anisotropic broadenings. Two ground-breaking techniques that were developed towards this end are double rotation (DOR) and dynamic angle spinning (DAS) NMR [1,2], methods that carry out the averaging of second-order quadrupolar interactions entirely by spatial manipulation of the frequency terms and therefore face some technical difficulties in their routine implementation. More recently an alternative has been proposed that by averaging anisotropies by means of both spatial and spin space manipulations relieves some of these technical difficulties [3]. This multiple-quantum magic-angle-spinning (MQMAS) NMR experiment relies on the excitation of symmetric $-m \leftrightarrow +m$ MQ coherences and on their subsequent conversion to the central single-quantum observable, in order to realize a high resolution correlation that along a certain projection is free from second-order interactions. The simplicity of this technique has made it notably popular and applications have been reported on a variety of nuclei including sodium, rubidium, aluminum, oxygen, boron, niobium, chlorine and cobalt, species with

* Corresponding author. Fax: +972 8 934 4123; e-mail: civega@wis.weizmann.ac.il

0009-2614/99/$ - see front matter
PII: S0009-2614(99)00446-7

different spin quantum numbers that are characterized by a variety of coupling environments [4–10].

The basic irradiation scheme used in MQMAS experiments involves two pulses: a first one that excites the MQ coherence, and a second that converts this coherence into a single-quantum observable (Fig. 1A) [11–14]. Several studies have focused on how spinning speed, decoupling, rf power and pulse widths will affect the efficiency of this two-pulse MQMAS experiment [11–18]. Alternatives to this basic scheme including the use of Z-filtering, split–t_1 procedures, synchronized data acquisition, and a choice of pulse widths set according to the duration of the rotor period, have also been discussed and exemplified [19–22]. Furthermore, all these investigations emphasizing the use of rectangular continuous wave (CW) pulses have been recently complemented by alternative methodologies including triangular and composite pulses which were also successfully demonstrated [23–25].

In spite of all this remarkable progress an inherent problem that still affects many MQMAS NMR experiments is their relative poor signal-to-noise ratio, stemming mainly from the relative inefficiency of the conversion step in which MQ coherences are transformed into single-quantum observables. From the earliest MQMAS studies it was realized that using the highest possible rf fields will in most cases enhance the efficiency of this process and thereby increase the observable MQMAS signal, and this simple albeit 'brute force' observation has been one of the main criteria driving the manufacturing of dedicated hardware for this experiment. Yet it seems likely that pulse sequence refinements based on a better understanding of the spins behavior under the effects of the relevant nuclear spin Hamiltonians will eventually lead to even further improvements in the performance of the experiments. The present paper reports on one such additional improvement, based on the use of amplitude-modulated (AM) pulses for the conversion of the MQ coherences into single-quantum magnetizations. This approach was explored due to its proven efficiency in previous half-integer single crystal studies, and it was theoretically found to increase by a factor of ca. 3 the amount of MQMAS signal detected from spin-3/2 powders under prototypical conditions. These predictions were quantitatively corroborated by a series of experiments performed on model spin-3/2 compounds which involved a discrete four-level analog of the continuous AM shaping scheme.

2. Experimental

All experiments presented in this work were performed using sequences derived from the standard two-pulse MQMAS acquisition scheme. Since attention focused on improving the efficiency of the conversion process the first excitation pulse was in all experiments set to a rectangular CW profile; the amplitude of the second pulse was then modulated in one set of experiments and kept constant in a second, reference set (Fig. 1). Experiments were performed on a variety of samples in a laboratory-built 200 MHz NMR spectrometer as well as on a Bruker DSX-300 MHz machine, and in all cases involved the usual MQMAS States-type phase-cycling selection scheme [11,14]. Unidimensional tests on the potential advantages resulting from AM pulses were carried out using MAS at a constant spinning speed of 6.5 kHz and a 104 kHz peak rf field. In these experiments a 5 μs CW pulse was used for the MQ coherence excitation, and the performance of an optimum CW conversion pulse (2 μs long) was compared against an rf pulse possessing an ampli-

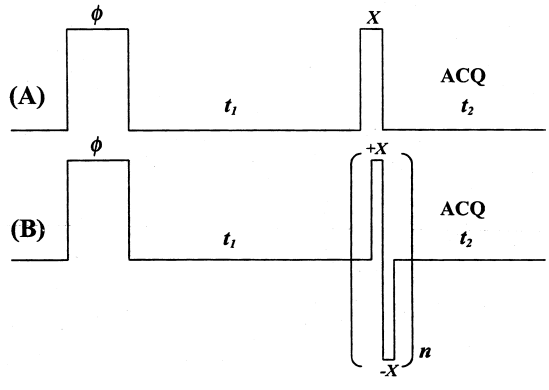

Fig. 1. Pulse schemes involved in the conventional two-pulse MQMAS experiment (A), and in the amplitude-modulated (AM) version introduced in this work (B). The phase cycling employed for the first pulse and the receiver demodulation were, respectively, $\phi = 0, 60, 120, 180, 240, 300$ and $\phi_{Rx} = 0, 180$ [11]. One unit of the AM scheme is illustrated in (B), this was repeated n times and n was optimized for best experimental performance.

tude profile of $(0, 104, -104, 0)_n$ kHz, with each of these levels lasting for 1 μs and the overall profile chosen as an approximation to an ideal cosine-shaped AM pulse. The number of times n that this four-level block was repeated was optimized for the different nuclei studied: $n = 4$ for ^{23}Na and $n = 5$ for ^{87}Rb experiments. Similar results were obtained when a $(0, 104, 0, -104)_n$ kHz AM scheme was assayed. Two-dimensional MQMAS NMR spectra on sodium sulfate and rubidium chromate were also collected in order to verify the sensitivity enhancement and monitor the potential line shape distortions which might arise from using the AM conversion pulses. These acquisitions employed 128 t_1 increments with 10 μs dwell time, MAS at a rate of 15 kHz, rf fields of 104 kHz, initial excitation pulses of 5 μs, and AM pulse parameters as described for the 1D NMR acquisitions. The number of scans acquired per t_1 increment was 6 and 18 with a recycle delay of 2 s and 500 ms, for the sodium and rubidium samples respectively.

3. Results and discussion

The present attempt to improve the performance of MQMAS NMR is based on earlier work by Vega and Naor [26], who used a fictitious spin $-1/2$ description of MQ quadrupolar spectroscopy to focus on rf manipulations inside a spin-$3/2$ manifold. That study discussed the possibility of effectively accomplishing interconversion between single- and triple-quantum coherences by simultaneous irradiation of the $|\pm 1/2\rangle \leftrightarrow |\pm 3/2\rangle$ single-quantum satellite transitions, an experiment which can be achieved using a pair of rf pulses oscillating at equidistant frequencies from the on-resonance condition, or a single on-resonance but amplitude-modulated pulse. The latter alternative is usually easier to implement, and was in fact demonstrated by Vega and Naor on static single crystals of sodium ammonium tartrate characterized by well-defined quadrupolar frequencies. By the same principles an optimized AM rf pulse could be useful in MQMAS for converting triple-quantum coherences into single-quantum observables, although in this case the scenario is complicated by the powder distribution of quadrupolar frequencies and by the time dependence of the interactions brought about by sample spinning. Yet as is demonstrated in the following paragraphs, the fact that the intensities of the outer satellite transitions peak at frequencies notably far from on-resonance and that the optimized nutation pulse widths end up being short compared to the rotor period, combine to make the performance of the AM conversion pulse notably superior to that of its CW counterpart.

To carry out a preliminary check on the efficiency of the AM conversion scheme a series of exploratory numerical simulations were carried out. These focused on the evolution of a spin-$3/2$ powdered ensemble and involved solving by numerical means the Liouville–von Neuman rate equation [27]

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = \mathrm{i}[\rho, \mathscr{H}] \tag{1}$$

where ρ and $\mathscr{H}$ are the density matrix and Hamiltonian of the system. The formal solution of Eq. (1) was calculated as

$$\rho(t) = \mathscr{U}^{-1}(t,0)\,\rho_0\,\mathscr{U}(t,0) \tag{2}$$

where ρ_0 is the initial density matrix and the evolution operator $\mathscr{U}(t,0)$ was computed as a time-ordered product

$$\mathscr{U}(0,t) = \mathscr{T}\exp\left[-\mathrm{i}\int_0^t \mathscr{H}(t')\,\mathrm{d}t'\right]. \tag{3}$$

The rotating-frame Hamiltonian considered for these propagations was

$$\mathscr{H}(t) = \mathscr{H}_{\mathrm{int}}(t) + \mathscr{H}_{\mathrm{rf}}(t) \tag{4}$$

where the internal component $\mathscr{H}_{\mathrm{int}}(t)$ containing first- and second-order couplings $\omega_Q^{(1)}$, $\omega_{Q,\mathrm{m}}^{(2)}$ rendered time-dependent because of the spinning is

$$\begin{aligned}\mathscr{H}_{\mathrm{int}}(t) &= \omega_Q^{(1)}(\alpha,\beta,\gamma,t)\left[3I_z^2 - I(I+1)\right] \\ &\quad + \omega_{Q,1}^{(2)}(\alpha,\beta,\gamma,t)\left[4I(I+1) - 8I_z^2 - 1\right]I_z \\ &\quad + \omega_{Q,2}^{(2)}(\alpha,\beta,\gamma,t)\left[2I(I+1) - 2I_z^2 - 1\right]I_z,\end{aligned} \tag{5}$$

while the rf interaction is given by

$$\mathscr{H}_{\mathrm{rf}}(t) = \omega_{\mathrm{rf}}(t)\,I_\phi \tag{6}$$

representing a pulse of constant phase ϕ but time-dependent amplitude ω_{rf}. The exact forms of the $\omega_Q^{(i)}$

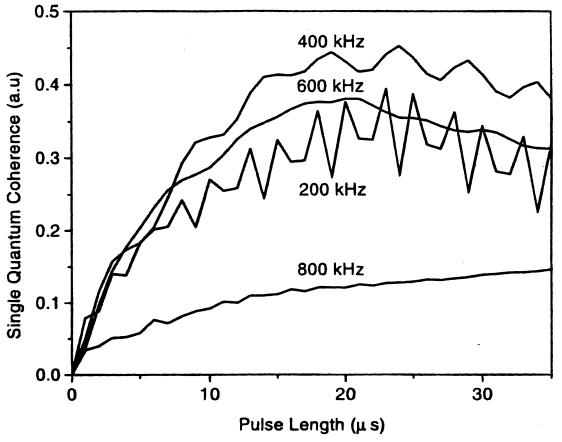

Fig. 2. Generation of central transition single-quantum coherence by a time-dependent conversion pulse $\omega_{rf}(t) = \omega_1 \cos(\omega_m t)$ from a triple-quantum coherent state, as a function of the modulation frequency ω_m of the irradiation. In these simulations the triple-quantum coherence was set to one for all orientations as initial condition before the pulse, a maximum amplitude $\omega_1/2\pi = 80$ kHz and a spinning rate $\omega_r/2\pi = 8$ kHz were assumed, and a single site with $e^2qQ/h = 2.4$ MHz, $\eta_q = 0$ and $\omega_0/2\pi = 52$ MHz was considered. The typical value given by a CW pulse scheme for the single quantum coherence under identical conditions is 0.12.

expressions have been given in detail elsewhere [28,29]; they depend on the Euler angles (α, β, γ) defining the principal axis system of the quadrupole tensor in the rotor frame, on the Larmor frequency ω_0, as well as on the sample spinning frequency ω_r. Chemical shift and off-resonance offsets were thus ignored in this analysis although their effects, when small, can be expected to be similar to those brought about by the $\omega^{(2)}_{Q,m}$ terms. During free evolution $\omega_{rf}(t) = 0$, the Hamiltonian is then diagonal and the propagation of the system can be computed using a direct analytical integration. On the other hand, when rf pulses are introduced the spin Hamiltonian is non-diagonal and its stepwise numerical diagonalization and integration becomes necessary; ten steps per μs were found sufficient for obtaining a converging behavior in these spin evolution calculations. In all

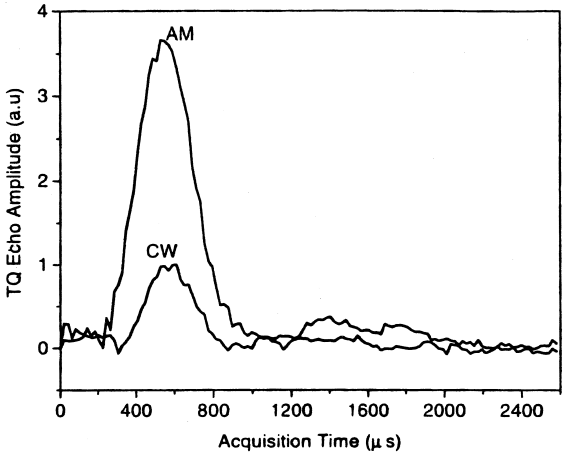

Fig. 3. Comparison between the ^{23}Na MQMAS signals obtained on Na_2SO_4 (7.1 T) using the conventional CW/CW pulse sequence, and after replacing the second pulse with a $(0, \omega_1, -\omega_1, 0)_n$ AM profile. In both cases peak rf fields of 104 kHz, an interpulse delay of 700 μs as constant t_1, and a spinning speed of 6500 Hz were used.

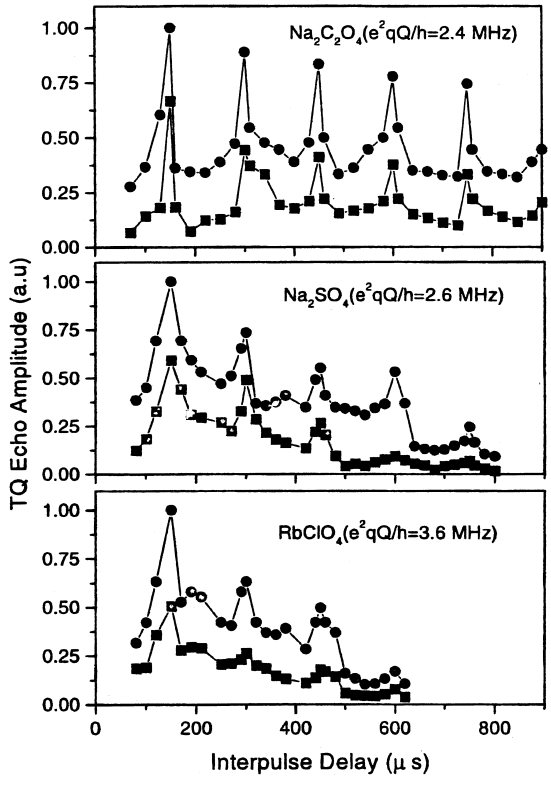

Fig. 4. Experimental triple-quantum echo amplitudes observed upon using the CW/CW (squares) and CW/AM (circles) two-pulse schemes, as a function of the interpulse delay t_1. Data were collected at 7.1 T on the sodium oxalate sample and at 4.7 T for the sodium sulfate and rubidium perchlorate samples. In all cases experiments were done using an rf field of 104 kHz and a spinning speed of 6.5 kHz.

cases, calculations employed 1154 different powder orientations to account for the anisotropy of the interactions [30].

Fig. 2 shows a series of nutation profiles illustrating how triple- to single-quantum conversion processes are expected to proceed for a spin-$3/2$ powder acted upon by a cosine-modulated pulse, as a function of the pulse modulation frequency ω_m. This figure evidences that, at least for these typical ^{23}Na coupling and acquisition parameters, a high single-quantum conversion efficiency can be expected from a suitably shaped AM pulse. Also worth noting is the fact that, in agreement with the arguments discussed earlier regarding the relation between the MQ conversion process and the excitation of $|\pm 3/2\rangle \leftrightarrow |\pm 1/2\rangle$ transitions, the intensity of the MQMAS observable grows as the pulse modulation frequency ω_m approaches the 'cusps' of the satellite powder line shapes (located at $\pm e^2qQ/4h$ for a symmetric spin-$3/2$ quadrupole) and after that it experiences a decrease. A deeper analysis as to why and how AM conversion pulses achieve an enhancement of the MQMAS sensitivity when compared with CW irradiation will be presented in an upcoming publication [31].

To further substantiate these theoretical predictions, a series of experimental comparisons between CW-based pulse sequences and counterparts incorporating AM conversion pulses were carried out. Due to the potential difficulties that commercial instruments face in generating smooth high-power AM pulses, the shaped-pulse experiments assayed were based on square-wave profiles, easily generated with standard rf gates and phase shifters. Two such profiles were tested, $(0,\ \omega_1,\ -\omega_1,\ 0)_n$ and $(\omega_1,\ 0,\ -\omega_1,\ 0)_n$, with each of these levels arbitrarily set to last for 1 μs and their optimal n value determined experimentally. No significant performance differences were observed between these two schemes, a behavior which stems from similarities in their frequency-domain Fourier components and whose origin we have elucidated [31]. Fig. 3 compares the central transition time-domain signal afforded by a $(0,\ \omega_1,\ -\omega_1,\ 0)_n$ AM MQMAS sequence with the signal intensity resulting when using the conventional CW-based sequence. Identical MQ excitation

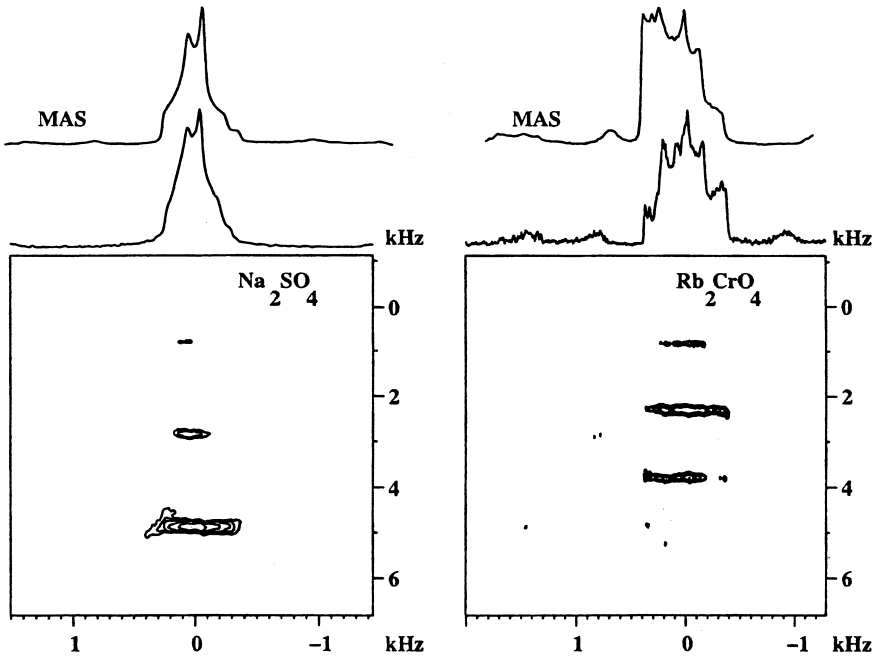

Fig. 5. Sheared 2D MQMAS NMR spectra of sodium sulfate (left) and rubidium chromate (right) obtained using the AM conversion pulses at 7.1 T. Horizontal axes represent the MAS dimension and vertical axes represent the MQMAS dimension; the spectra on top of the anisotropic slices correspond to the experimental MAS powder patterns acquired under identical conditions with a 90° 'solids' pulse.

conditions, MQ t_1 evolution delays (set exactly to five full rotor revolution periods) and rf power were employed in both experiments. As can be seen from these data there is a definite advantage to the use of AM pulse schemes when attempting to convert evolving triple-quantum coherences into single-quantum observables.

Further experimental confirmation of these improvements is presented in Fig. 4, which compares the MQMAS echo amplitudes yielded by purely-CW and CW/AM-based two-pulse sequences as a function of the interpulse delay t_1. This figure, which shows the typical rotor modulations known to give intense sidebands along the indirect dimension of MQMAS spectra [32], encompasses a variety of samples and data collected employing different spectrometers and probeheads. Nevertheless, in all cases the data clearly reveal that a large signal enhancement is achieved when using the AM conversion pulses. Similar enhancements materialize when these data are processed into complete 2D MQMAS NMR sheared spectra (Fig. 5). Peaks in these spectra are 300–350% more intense than those observed in their optimized CW counterparts, and the applicability of the AM conversion technique to samples such as Rb_2CrO_4 demonstrates its promise even when relatively large shielding anisotropies are present. In addition to their high-resolution features these spectra reveal featured anisotropic line shapes that, as was the case with the conventional two-pulse CW sequence, can be reliably analyzed towards the detailed extraction of the quadrupole coupling parameters.

4. Conclusions

An alternative methodology for acquiring MQMAS NMR data based on the use of AM conversion pulses was introduced and demonstrated. Preliminary results reveal considerable promise for this new approach, with signal enhancements in excess of 300% and undistorted final MQMAS line shapes for spin-3/2 powders. Further investigations are being carried out to extend the applicability of this approach to higher spin systems, larger quadrupolar couplings and other orders of MQ coherence. An extensive search is also under way to obtain general amplitude and phase modulated pulse schemes that will provide the optimum effectiveness in both the excitation and conversion of MQ coherences, as well as a more lucid picture of the spin physics characterizing these pulse sequences. The incorporation of these strategies into other quadrupolar NMR experiments such as TRAPDOR and REAPDOR [33,34] is also being explored.

5. Note added in proof

While this paper was being reviewed an MQMAS experiment relying on similar physical principles but utilizing double frequency sweeps for the MQ conversion, was proposed and successfully demonstrated by Kentgens and Verhagen [35].

Acknowledgements

The authors would like to thank the US–Israeli Binational Science Foundation for research funding. L.F. thanks the Weizmann Institute for a Meyerhoff Visiting Professorship (1998), as well as the US National Science Foundation (DMR-9806810 and CHE-9841790) and the A.P. Sloan Foundation for support.

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