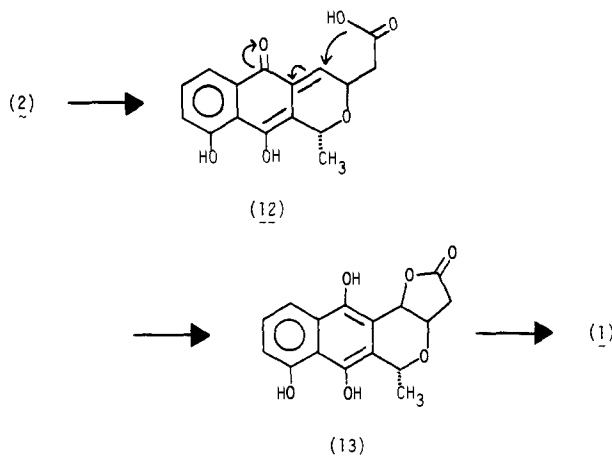


been reported to give nanaomycin D,<sup>3</sup> and indeed, treatment of our synthetic nanaomycin A with air in methanolic solution gave a racemic mixture of kalafungin and nanaomycin D (**1**)<sup>3</sup> (mp 135 °C dec). A plausible mechanism involves the quinone methide intermediate **12**<sup>6</sup> in the oxidative process. Intramolecular conjugate addition of the carboxylic acid into the enone would then give the quinol lactone **13**, which could be readily oxidized to give the quinone.



The IR, NMR, mass, and UV spectra, as well as the TLC behavior of the synthetic nanaomycin A and kalafungin-nanaomycin D, were indistinguishable from those of the respective natural products.<sup>18</sup>

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- (18) We are grateful to Dr. Ōmura of the Kitasato Institute for providing us with an authentic sample of nanaomycin A and to Dr. Whitefield of The Upjohn Co. for an authentic sample of kalafungin. The authors thank Drs. M. Marx, J. A. Edwards, and J. G. Moffatt for critically reading the manuscript and for helpful discussion and encouragement throughout this project. We are also grateful to the Syntex Analytical Department for their expert help.

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#### Transverse Relaxation of Multiple Quantum Coherence in Nuclear Magnetic Resonance as a Probe of Molecular Motion

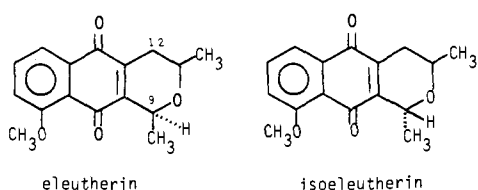
Sir:

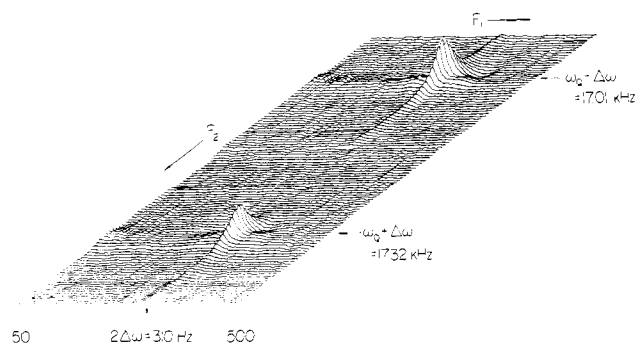
The development of pulse techniques for observations of zero and multiple quantum (MQ) coherences in NMR<sup>1-3</sup> has opened new perspectives for relaxation studies of multilevel spin systems. Though not directly observable, MQ coherences may be stimulated by appropriately tailored pulses.<sup>1-5</sup> Their time evolution is characterized by a decay similar in kind to the transverse ( $T_2$ ) decay of normal 1Q magnetizations, but the decay rates are quantitatively different. In combination with conventional longitudinal and transverse relaxation measurements, the MQ decay rates therefore provide a powerful tool for detailed studies of relaxation pathways and molecular dynamics. In this communication, we demonstrate the utility of double quantum line widths for the determination of spectral densities of motion in two single deuteron systems, CDCl<sub>3</sub> and DC≡C—C≡N, partially ordered in a nematic solvent.

The use of two-dimensional Fourier transform techniques<sup>1,6,7</sup> is essential for measurements of MQ decay rates in all but the very simplest<sup>3,4</sup> spin systems. After an initial excitation, the MQ coherences are allowed to evolve for a time  $t_1$ . The application of a "monitoring" pulse generates conventional (1Q) magnetizations with amplitudes which depend on the phases of the "invisible" coherences at  $t = t_1$ .<sup>1,4</sup> The free induction decay, which develops during the subsequent period  $t_2$ , yields the usual spectrum in a frequency domain  $F_2$ . A series of such spectra obtained at regular increments of  $t_1$  may be subjected to a second Fourier transformation with respect to  $t_1$ . The modulation due to MQ coherences is thereby translated into resonance peaks in the frequency domain  $F_1$ .

The NMR spectrum of a single partially ordered deuteron consists<sup>8</sup> of two nondegenerate ( $1 \rightarrow 0$  and  $0 \rightarrow -1$ ) 1Q transitions at  $\omega_0 \pm \omega_Q$ . The double quantum (2Q) coherence of a simple three-level system may be readily excited<sup>4</sup> by a "soft" pulse applied at an offset  $\Delta\omega$  from the center  $\omega_0$  of the doublet. Provided that  $\Delta\omega \ll \omega_1 \ll \omega_Q$ , the largest 2Q coherence is obtained for a pulse width  $t_{p1} = \pi\omega_Q/2\omega_1^2$ .<sup>4</sup> The monitoring pulse should ideally fulfill the condition  $t_{p2} = \pi/2\omega_1$  with  $\omega_1 \gg \omega_Q$ . Alternatively, a weak ( $\omega_1 \ll \omega_Q$ ) audiomodulated ( $\omega_M \approx \omega_Q$ ) monitoring pulse may be used.<sup>9</sup> Conditions for observation of the 2Q coherence for a single deuteron are not very stringent.<sup>4</sup> Any effect of spurious excitation of transverse 1Q magnetization by the first pulse may be suppressed by use of phase alternation.<sup>5,10</sup> Also, a monitoring pulse with  $\omega_1 \approx \omega_Q$  was found to be adequate.

An example of a two-dimensional spectrum of a liquid crystalline solution of DCCCN is shown in Figure 1. A section (540 Hz = 110 points) of the folded, phase corrected, 1Q





**Figure 1.** Two-dimensional Fourier transform spectrum of 10 mol % DCCCN in Merck Phase V at 30.5 °C. The  $F_2$  domain shows a section (540 Hz) of the regular NMR spectrum folded about the transmitter frequency positioned at  $\Delta\omega = 155$  Hz off resonance. The  $F_1$  domain presents the double quantum signal at  $F_1$  of  $2\Delta\omega$ . The experiment was performed at 9.21 MHz in  $\sim 2$  h, using 8k data points to cover a spectral width of 20 KHz in the  $F_2$  domain. The evolution period  $t_1$  was incremented in 200 steps of 1 ms. For the first pulse,  $\omega_1 = 4.6$  kHz ( $\sim\omega_Q/4$ ) and  $t_{p1} = 200$   $\mu$ s, while for the monitoring pulse,  $\omega_1 = 17$  kHz and  $t_{p2} = 15$   $\mu$ s.

spectrum appears along the  $F_2$  axis. The  $F_2$  widths of the two lines are influenced<sup>11</sup> not only by the transverse decay rates  $R_2(1,0) = R_2(0,-1)$  and static field inhomogeneity, but also by thermal gradients which cause a spread in  $\omega_Q$ . The line separation in the folded spectrum equals twice the resonance offset,  $\Delta\omega = 155$  Hz. Along the  $F_1$  axis the double quantum phase coherence is observed as predicted.<sup>1,2,4</sup> at  $2\Delta\omega$  and the line is broadened by twice the static field inhomogeneity. Since the double quantum precession frequency does not depend on  $\omega_Q$ , the inhomogeneous broadening from thermal gradients is absent. This property has been exploited in several elegant deuterium studies of solid<sup>2,4,12</sup> and liquid crystals.<sup>13</sup>

By measurement of the line width in the  $F_1$  domain in Figure 1 and correcting for the static inhomogeneity ( $2\delta\omega_0 = 3.6$  Hz) we obtained  $R_2(1,-1) = 20 \pm 2$  s<sup>-1</sup> for a 10 mol % solution of DCCCN in Merck Phase V at 30.5 °C. A similar experiment yielded  $R_2(1,-1) = 13.4 \pm 1.4$  s<sup>-1</sup> for 10 mol % CDCl<sub>3</sub> in the same solvent at 32.3 °C.

Relations between Redfield relaxation elements<sup>14</sup> for a single ordered deuteron and the three spectral densities of motion,  $J_0(0)$ ,  $J_1(\omega_0)$ , and  $J_2(2\omega_0)$ , have recently been published.<sup>11,15,16</sup> It may be shown that the 2Q coherence decay rate  $R_2(1,-1)$  is given by a single Redfield relaxation element:

$$R_2(1,-1) = (3\pi^2/20)(e^2qQ/h)^2\{J_1(\omega_0) + 2J_2(2\omega_0)\} \quad (1)$$

A nonselective inversion recovery experiment yields the quantity  $J_1(\omega_0) + 4J_2(2\omega_0)$  while  $J_1(\omega_0)$  can be obtained separately using selective pulses to monitor the difference magnetization created by selective inversion of either doublet component.<sup>11,17</sup> From such spin lattice relaxation experiments we have obtained<sup>18</sup>  $J_1(\omega_0) = 170 \pm 10$  ps,  $J_2(2\omega_0) = 83 \pm 5$  ps for DCCCN and  $J_1(\omega_0) = 161 \pm 11$  ps,  $J_2(2\omega_0) = 85 \pm 7$  ps for CDCl<sub>3</sub>. Using these values, eq 1, and published values<sup>19,20</sup> for  $(e^2qQ/h)$  we calculate  $R_2(1,-1) = 20.1 \pm 0.8$  s<sup>-1</sup> for DCCCN and  $R_2(1,-1) = 13.3 \pm 0.7$  s<sup>-1</sup> for CDCl<sub>3</sub>, in excellent agreement with the values observed in the double quantum experiment.

It appears, then, that accurate double quantum decay rates may be obtained, provided that the static field inhomogeneity is known and not too large. Otherwise, echo techniques<sup>21,22</sup> must be used. In the present case no new information was obtained, but the 2Q experiment may be viewed as a valuable check on the interesting observation that  $J_1(\omega_0) > J_2(2\omega_0)$  even though the motion appears to be well within the extreme narrowing limit ( $\tau_c = 1/2J_0(0)$  with present definitions). In ordered systems with two deuterons, the complete characterization of the molecular dynamics requires knowledge of MQ

relaxation rates.<sup>23</sup> A general discussion of complex spin systems with an elegant application to paramagnetic relaxation will soon be published by Wokaun and Ernst.<sup>22</sup>

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## A MINDO/3 Study of Some Hydrogen-Bonded Systems

Sir:

A study of some sample hydrogen-bonded systems was made using the MINDO/3 geometry optimizing method of Bingham, Dewar, and Lo.<sup>1</sup> The systems chosen for study are tabulated in Table I along with the heats of formation of the monomer and dimer.

The calculations for the hydrogen-bonded dimers were performed using the optimized geometries of the monomers as found by the MINDO/3 method.<sup>1</sup> The monomers were then set at orientations predicted to be the most stable according to ab initio studies. The intermolecular distance between the monomers was optimized by initiating the distance  $R_{x-x'}$  at 1.00 Å less than the ab initio best  $R_{x-x'}$  listed in Table I. The distance  $R_{x-x'}$  is the distance between the second row atoms involved in the hydrogen bond which can be represented as  $x \cdots H - x'$ . It can be seen from the tabulated results that the optimization procedure of MINDO/3 using standard options as given in the program separates the monomers to a distance beyond that considered normal for hydrogen bonding. At these intermolecular distances which are predicted to be the most stable, it can be seen that the dimer system has either the same stability as two independent monomers or is less stable than two isolated monomers.