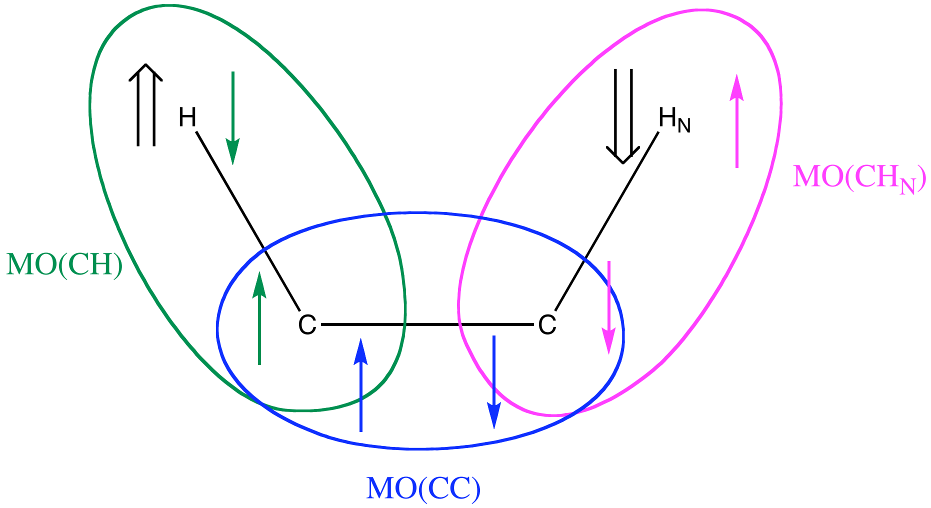
Preferred ^3J Spin-Spin Coupling



Fermi Contact: The nuclear spin prefers to be antiparallel relative to spin of the proximate electron.

Spin Polarization of "paired electrons": Pauli rule applies to electrons that occupy (almost) the same orbital. If the beta electron spends more time at H, then the alpha electron spends more time at C.

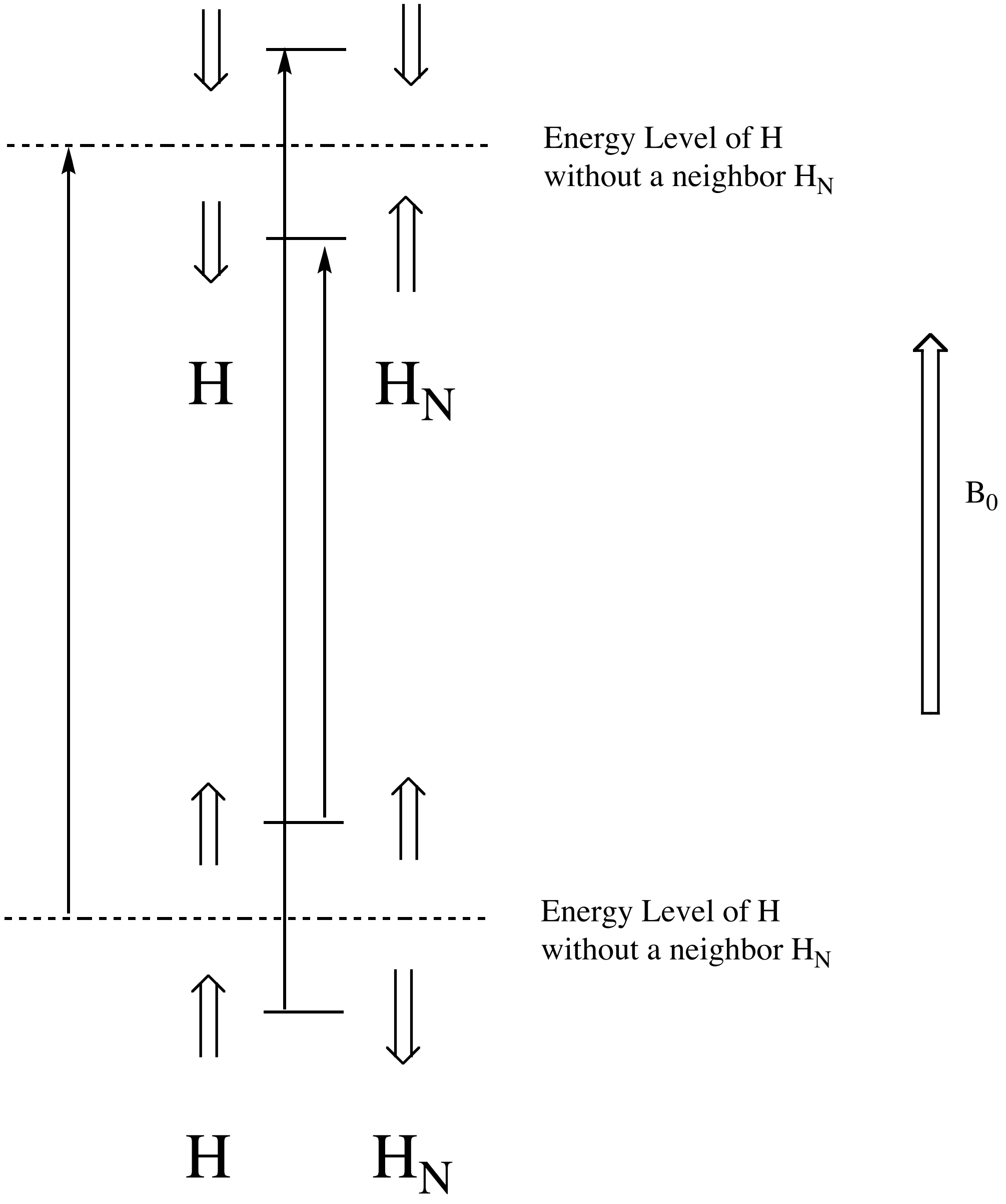
Hund's Second Rule: Maximize the multiplicity in the region around any given atom. If there is more alpha electron at C because of MO(CH), then it is best if all other MOs that involve C are spin polarized such that there is maxumum spin in that C-region.

Apply these rules...

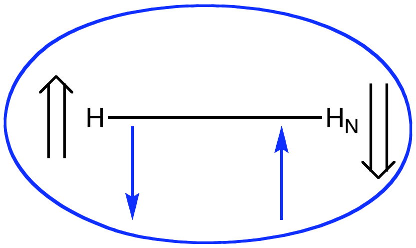
^3J spin -spin coupling is best if the nuclear spin of the neighboring H is antiparallel to the nuclear spin of the observed H

Energy Levels with Spin-Spin Coupling

Flip H, do not flip H_N!



Preferred ^1J Spin-Spin Coupling



MO(HH)

Fermi Contact: The nuclear spin prefers to be antiparallel relative to spin of the proximate electron.

Spin Polarization of "paired electrons": Pauli rule applies to electrons that occupy (almost) the same orbital. If the beta electron spends more time at H, then the alpha electron spends more time at H_N.

Apply these Fermi Contact rule one more time.

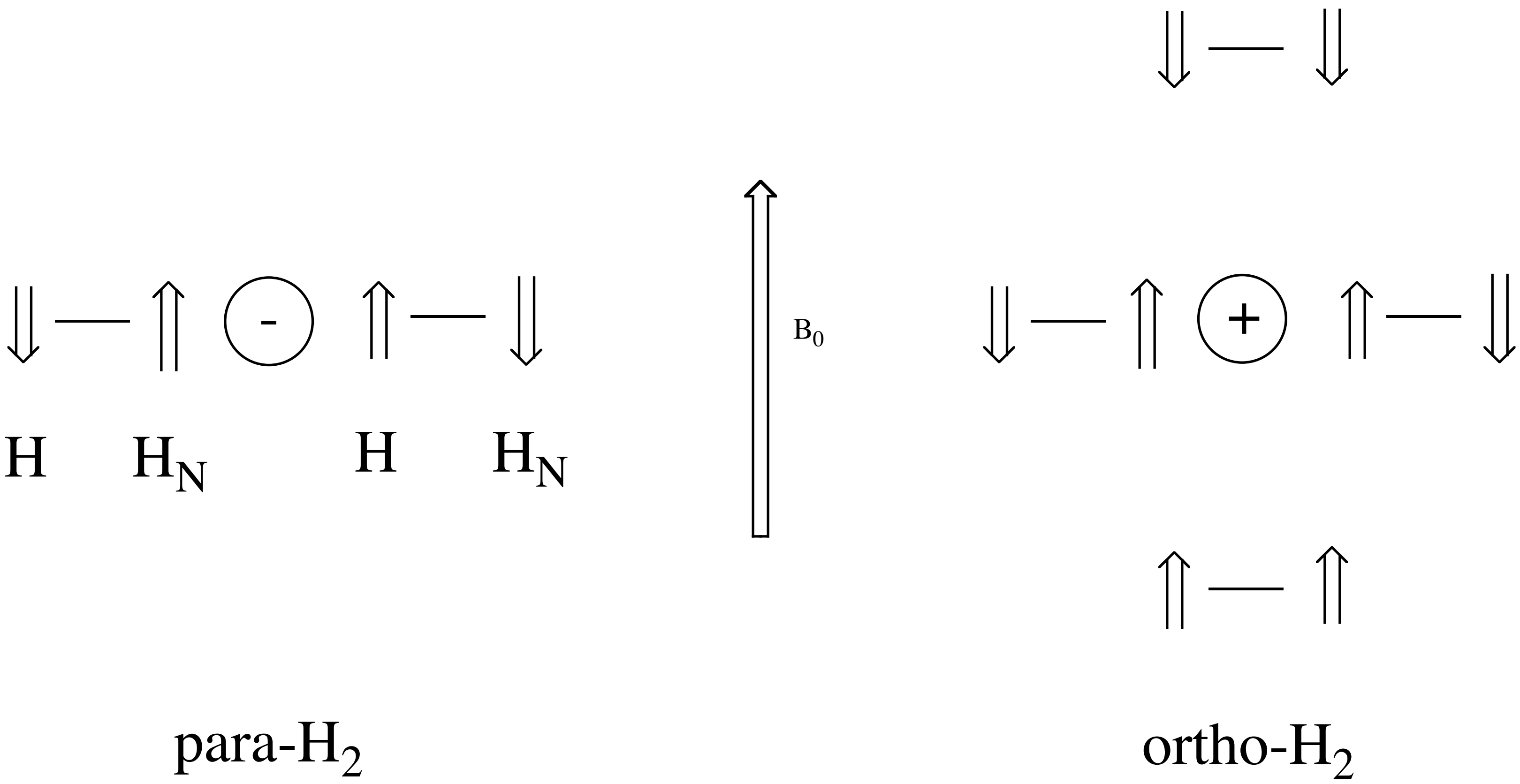
^1J spin-spin coupling is best if the nuclear spin of the neighboring H is antiparallel to the nuclear spin of the observed H.

This is normal H_2. There is no overall electron spin, and there is no overall nuclear spin. This is called ortho-H_2.

One more complication: The Hs are not distinguishable and, hence, we need to consider linear combinations for the nuclear spins.

[(up-down) + (down up)] TRUE "singlet"
[(up down) - (down up)] PART of "triplet", (up up), (down down)

Energy Levels with Spin-Spin Coupling, para- and ortho-H_2



Para-Hydrogen Enrichment and Hyperpolarization

DANIEL CANET,[1] CHRISTIE AROULANDA,[1] PIERRE MUTZENHARDT,[1] SILVIO AIME,[2]
ROBERTO GOBETTO,[2] FRANCESCA REINERI[2]

[1] *Méthodologie RMN (UMR CNRS-UHP 7565), Université Henri Poincaré, Faculté des Sciences, BP 239, 54506 Vandoeuvre-lès-Nancy Cedex, France*
[2] *Università degli Studi di Torino, Dipartimento di Chimica I.F.M. and Center for Molecular Imaging, Via P. Giuria 7, 10125 Torino, Italy*

ABSTRACT: This article begins with general considerations about enrichment of hydrogen gas into its para isomer (corresponding to nuclear spins in the singlet state); this is a necessary condition to obtain hyperpolarization from transfer of the relevant population excess. This transfer is generally mediated by a hydrogenation reaction such that the two protons become nonequivalent. The energy level populations of this new spin system can be calculated unambiguously using a density matrix formalism. This formalism is reviewed, and the authors propose a simple method that leads to the spin state after the hydrogenation reaction and the insertion of the sample in the NMR magnet. The effect of radiofrequency pulses is also considered. © 2006 Wiley Periodicals, Inc. Concepts Magn Reson Part A 28A: 321–330, 2006

KEY WORDS: hydrogen; nuclear spin isomers; hyperpolarization; NMR sensitivity enhancement

INTRODUCTION

For more than 30 years, it has been known that the sensitivity of the NMR experiment can be increased (up to a factor of 10^4–10^5) by means of para-enriched hydrogen (p-H_2) inserted in a molecule at two nonequivalent positions by an appropriate chemical reaction. This hydrogenation reaction (generally using homogeneous catalytic processes) can be performed outside the magnet of the NMR machine (ALTADENA experiment) or inside (PASADENA experiment) (*1–9*). We do not go into the details of those experiments, but rather concentrate on the hyperpolarization phenomenon.

One generally considers that the spin state populations in the observed molecule are represented by the so-called Boltzmann equilibrium condition. Consequently, as the intensity of a NMR transition is proportional to the difference δ in population between the spin states involved in the considered transition (δ is of the order of 10^{-5}), the signal intensity is usually low and, subsequently, the sensitivity of NMR spectroscopy is poor. This weak sensitivity represents a major drawback for this technique. However, if the difference δ could be increased by a factor of δ^{-1}, then the intensity of the associated transition should increase dramatically. This is what happens when a

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Correspondence to: Daniel Canet; E-mail: Daniel.Canet@rmn.uhp-nancy.fr

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hydrogenation reaction occurs on a substrate, but with hydrogen preliminary enriched in its para isomer, called parahydrogen.

To understand how these hydrogenation products exhibit such a huge NMR sensitivity enhancement, we first define the two nuclear spin isomers of the hydrogen molecule in terms of nuclear spin wave functions (*10*). From the para-hydrogen spin functions the corresponding density operator is derived: this allows us to introduce a method to calculate the density matrix for the spin system of the parahydrogenated molecules (i.e, the products obtained by para-enriched hydrogen reaction). In that way, we are able to predict the relative intensities of the lines in the ^{1}H NMR spectra.

PARAHYDROGEN AND ORTHOHYDROGEN SPIN FUNCTION

For a single spin ½ system, there exists two states represented by the wave functions α and β, which are eigenfunctions of an operator associated with one component (say z) of the spin momentum: $\hat{I}_z\alpha = (1/2)\alpha$; $\hat{I}_z\beta = (-1/2)\beta$. These two wave functions are necessarily orthogonal (in the sense that their scalar product is zero) and are normalized (in the sense that the scalar product of α by itself or of β by itself is equal to 1).

Now consider two equivalent spins ½, denoted by A and A', as the two protons in the hydrogen molecule. The four states of this spin system could be represented by the orthonormalized wave functions $\alpha_A\alpha_{A'}$, $\alpha_A\beta_{A'}$, $\beta_A\alpha_{A'}$, and $\beta_A\beta_{A'}$. However, due to the equivalence of the two spins and because the physical meaning of a wave function rests on the product of this function by its complex congugate, appropriate wave functions should be either symmetric or antisymmetric with respect to the permutation $\mathcal{P}$ of the two spins. It is obvious that $\alpha_A\alpha_{A'}$ and $\beta_A\beta_{A'}$ are symmetric but that $\alpha_A\beta_{A'}$ and $\beta_A\alpha_{A'}$ are neither symmetric nor antisymmetric. However, it is well known that the sum and the difference (multiplied by a factor of $1/\sqrt{2}$ for normalization) of two orthonormalized wave functions lead to two new orthonormalized wave functions. We thus obtain from $\alpha_A\beta_{A'}$ and $\beta_A\alpha_{A'}$ two new functions: $(1/\sqrt{2})(\alpha_A\beta_{A'} + \beta_A\alpha_{A'})$, which is symmetric, and $(1/\sqrt{2})(\alpha_A\beta_{A'} - \beta_A\alpha_{A'})$, which is antisymmetric with respect to the operation $\mathcal{P}$. Altogether, the four appropriate wave functions for a system of two equivalent spins ½ can be arranged into the following two categories:

1) $\alpha_A\alpha_{A'}$; $(1/\sqrt{2})(\alpha_A\beta_{A'} + \beta_A\alpha_{A'})$; $\beta_A\beta_{A'}$. These are the symmetric wave functions constituting what is called the triplet state (three distinct states that possess the same energy); and

2) $(1/\sqrt{2})(\alpha_A\beta_{A'} - \beta_A\alpha_{A'})$. This is the antisymmetric wave function corresponding to what is called the singlet state.

Now, looking at the total angular momentum of the hydrogen molecule, the rotation molecular angular momentum has to be taken into account in addition to all the spin angular momenta, including nuclear and electronic spin angular momenta. Because the two electrons of the chemical bond are paired, the electron spins do not contribute. One is thus left with overall rotation and nuclear spins so that the wave function associated with the total angular momentum can be written as $\Phi = \Psi_J\Psi_N$, where Ψ_J stands for the wave function associated with the overall rotation and Ψ_N stands for the wave function associated with the nuclear spins. Ψ_N is then one of the four wave functions described previously (i.e., $\alpha_A\alpha_{A'}$; $(1/\sqrt{2})(\alpha_A\beta_{A'} + \beta_A\alpha_{A'})$; $\beta_A\beta_{A'}$, or $(1/\sqrt{2})(\alpha_A\beta_{A'} - \beta_A\alpha_{A'})$).

Φ must be antisymmetric with respect to the permutation $\mathcal{P}$ of the two hydrogen atoms (this is because hydrogen obeys the Fermi-Dirac statistics). As Ψ_J can be either symmetric or antisymmetric, the singlet nuclear spin wave function is associated with the symmetric rotation wave function, whereas the triplet wave functions are associated with the antisymmetric rotation wave function. Thus we end up with two different isomers, the one involving the singlet state, which corresponds to the isomer called parahydrogen (p-H_2), and the one corresponding to the triplet state, which corresponds to the other isomer called orthohydrogen. It turns out that the energy of the two isomers at room temperature is such that, owing to the number of wave functions in each state, there is 25% of parahydrogen and 75% of orthohydrogen. At lower temperatures, these proportions are changed. For instance, at liquid nitrogen temperature it is possible to reach identical proportions (50%) for both isomers. This means that leaving gaseous hydrogen at liquid nitrogen temperature, with a proper catalyst (e.g., charcoal or iron trioxide), an ortho-para conversion is allowed. Now, taking back this gas at room temperature and removing the catalyst, one has at hand a para-enriched sample that can be used for the purposes described in this article. It appears that the back conversion (para → ortho) is slow (in principle it is forbidden) and the decay time may vary from months or days to some hours, according to the surrounding state of matter (liquid or gaseous) (*11–17*). This leaves plenty of time for manipulation of the hydrogen molecule. Such a manipulation is necessary because the overpopulation of the singlet state cannot be used directly, no transition from the corresponding energy level being allowed. To take advantage of this overpopulation, it is mandatory to render nonequivalent the two protons, and this is usually achieved by a catalyzed hydrogenation reaction (*18–26*). Note that this article is not concerned with para → ortho conversion; for this aspect, the reader is referred to a recent review by Buntkowsky and colleagues (*14*).

The goal of this article is to use an appropriate tool—namely, the density operator (or the density matrix)—to explain how the addition of para-enriched hydrogen proceeds to an unsaturated substrate in terms of parahydrogen hyperpopulation redistribution among the product spin states.

A SURVEY OF THE DENSITY MATRIX AND DENSITY OPERATOR CONCEPTS

In a general way, the density matrix σ is defined by its elements σ_{kl}, which are equal to $\overline{c_k^* c_l}$, where c_k and c_l are the coefficients of the expansion (over an appropriate basis) of the wave function describing the actual state of the spin system (*10*). The asterisk denotes the complex conjugate, and the bar an ensemble average. Thus, if the selected basis for the description of the wave function is made of the time-independent Hamiltonian eigenvectors, the diagonal elements of the density matrix represent the population of energy levels, and nonzero off-diagonal elements reveal the presence of the so-called coherences. These off-diagonal elements are zero at thermal equilibrium because, in that case, only populations exist due to the lack of phase coherence among all spins constituting the sample under investigation. Coherences can be created by radio-frequency pulses or by the sudden change of the spin system as this occurs in the course of a hydrogenation process (see below). However, it is possible to define an operator to which this density matrix is associated; this one is the so-called density operator $\hat{\sigma}$, which can always be expanded over an operator basis, as will be shown hereafter with simple examples. The interest of the density operator $\hat{\sigma}$, in addition to the calculation of energy level populations, is its ability to describe the evolution of the spin system through the Liouville–von Neumann equation

$$\frac{d\hat{\sigma}}{dt} = i[\hat{\sigma}, \hat{H}(t)] \qquad [1]$$

where $[\hat{\sigma}, \hat{H}(t)]$ stands for the commutator of $\hat{\sigma}$ and $\hat{H}(t)$, the latter being the time-dependent Hamiltonian, including the effects of spin relaxation and of radio-frequency pulses.

Moreover, the density operator enables one to calculate the expectation value of any quantity G through the relation

$$\langle G \rangle = Tr(\hat{\sigma}\hat{G}) \qquad [2]$$

where $\hat{G}$ is the operator associated with the quantity of interest and Tr denotes the trace of the matrix, which is associated with $\hat{\sigma}\hat{G}$.

As a first example, consider the A_2 spin system of two equivalent spins ½ (e.g., the two nuclear spins of the hydrogen molecule, denoted in the following by A and A'). The eigenfunctions of the time-independent Hamiltonian can be written as $|1\rangle = \alpha\alpha$, $|2\rangle = (1/\sqrt{2})(\alpha\beta + \beta\alpha)$, $|3\rangle = (1/\sqrt{2})(\alpha\beta - \beta\alpha)$, $|4\rangle = \beta\beta$ (hereafter, subscripts A and A' are omitted; the first spin function refers to A and the second to A'). In the case of the hydrogen molecule, the singlet state $|3\rangle$ represents the para form. We assume that this state exists exclusively and that its magnitude is K. The density matrix expressed on the basis (| 1>, | 2>, | 3>, | 4>) is thus written

$$\sigma_{singlet} = K\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}. \qquad [3]$$

We can try to expand the corresponding density operator as a linear combination of operators or product operators (*27*). For this purpose, we present below some of these product operators in a matricial form: $\hat{E}$ is the identity operator; $\hat{I}_z$ the spin operator associated with the z component of the spin momentum; $\hat{I}_+$ and $\hat{I}_-$ are the usual raising and lowering operators $\hat{I}_\pm = \hat{I}_x \pm i\hat{I}_y$. Note that $I_+^A I_-^{A'} + I_-^A I_+^{A'} = 2(I_x^A I_x^{A'} + I_y^A I_y^{A'})$.

$$E = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},\ 4I_z^A I_z^{A'} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$I_+^A I_-^{A'} + I_-^A I_+^{A'} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad [4]$$

From the above matrices, it turns out that the density operator for the singlet state (i.e., para-hydrogen) can be expressed as

$$\hat{\sigma}_{singlet} = K[\hat{E}/4 - (\hat{I}_x^A \hat{I}_x^{A'} + \hat{I}_y^A \hat{I}_y^{A'} + \hat{I}_z^A \hat{I}_z^{A'})] \qquad [5]$$

As a second example, consider the AX spin system of two nonequivalent weakly coupled spins ½ (e.g., the two protons arising from p-H_2 in a molecule that has been subjected to a hydrogenation reaction). As the eigenfunctions of the time-independent Hamiltonian are now $|1\rangle = \alpha\alpha$, $|2\rangle = \alpha\beta$, $|3\rangle = \beta\alpha$, and $|4\rangle = \beta\beta$, the density matrix, constructed on this basis, can be written as

$$\sigma_{AX} = (K'/2)\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad [6]$$

In this case, the state of this spin system is represented by $\hat{\sigma}_{AX} = K'(\hat{E}/4 - \hat{I}_z^A\hat{I}_z^X)$.

THE STEADY-STATE DENSITY OPERATOR

Consider a hydrogenation reaction such that the two protons of the hydrogen molecule, initially forming an A_2 system, evolve toward an AX system. This means that these two protons become nonequivalent in the final molecule. Upon completion of the hydrogenation reaction, a steady state is necessarily reached. If we denote by $\hat{\sigma}_{st}$ the relevant density operator, it must be such that $(d\hat{\sigma}_{st}/dt) = 0$. In other words, by reference to Eq. [1], $\hat{\sigma}_{st}$ must satisfy the following equation:

$$[\hat{\sigma}_{st}, \hat{H}_{AX}] = 0 \qquad [7]$$

where

$$\hat{H}_{AX} = -\nu_A\hat{I}_z^A - \nu_X\hat{I}_z^X + J_{AX}(\hat{I}_x^A\hat{I}_x^X + \hat{I}_y^A\hat{I}_y^X + \hat{I}_z^A\hat{I}_z^X) \qquad [8]$$

ν_A and ν_X being the resonance frequencies of the two spins and J_{AX} their indirect coupling. Recall that if $|\nu_A - \nu_X|$ is much larger than J_{AX}, the third term in Eq. [8] can be simplified in $J_{AX}\hat{I}_z^A\hat{I}_z^X$.

As $\hat{\sigma}_{st}$ is expanded as a linear combination of operators or product operators, it is evident that those which will survive do commute with $\hat{H}_{AX}$. Referring to Eq. [5] in which A' is changed into X, one is led to the conclusion that only $K(\hat{E}/4 - \hat{I}_z^A\hat{I}_z^X)$ will satisfy this condition (the quantity $\hat{I}_z^A\hat{I}_z^X$, which commutes with the Zeeman part of the Hamiltonian, is called longitudinal spin order). This is the key to overpopulation retrieval. For a final molecule involving a spin system larger than *AX*, overpopulation may be transferred to other spins through the combination of the different commutators involved in an equation analogous to Eq. [7], with a Hamiltonian corresponding to the whole spin system. Some transfers are possible only in the case of an ALTADENA experiment (hydrogenation reaction in zero, or almost zero, static magnetic field). In such circumstances, the Hamiltonian is reduced to the J-coupling part and may thus induce more transfers as explained in recent publications (*28–30*). Nevertheless, as soon as the sample is placed in the strong magnetic field of the NMR spectrometer, the quantities that will survive are of the longitudinal spin-order type, unless this longitudinal spin order is transformed into magnetization by relaxation processes (*20*, *31*). This aspect is beyond the scope of this article.

ENERGY LEVEL POPULATIONS IN TWO SPIN ½ SYSTEMS WITH ENHANCED POLARIZATION ORIGINATING FROM PARA-HYDROGEN

Consider again the four states of an A_2 two spin ½ spin system. In the absence of any magnetic field, the four states have identical energy and henceforth the same populations as sketched in Fig. 1(a). In particular, the equilibrium population of the singlet state (corresponding to the spin function $(1/\sqrt{2})(\alpha\beta - \beta\alpha)$)) is $P_0 = 0.25$, whereas the population of the triplet state, corresponding to the other three spin functions, is $3P_0$ $(= 0.75)$.

In the presence of a static magnetic field, this energy diagram is modified as shown in Fig. 1(b), left. δ is the population excess of the lowest level (and the loss for the highest level), due to the Boltzmann distribution with respect to the $(1/\sqrt{2})(\alpha\beta - \beta\alpha)$ state (or equivalently $(1/\sqrt{2})(\alpha\beta + \beta\alpha)$ state) taken as a reference for the population calculations (at ambient temperature). The population of the singlet state remains the same (P_0) even if the spin system becomes AX (see Fig. 1, right) after, for instance, a reaction of hydrogenation that breaks the symmetry. This is because the energy levels corresponding to $(1/\sqrt{2})(\alpha\beta - \beta\alpha)$ and $(1/\sqrt{2})(\alpha\beta + \beta\alpha)$ are the same and are not modified by the magnetic field. Here, contrary to the case of para enrichment, the singlet state is not overpopulated. Therefore, despite the existence of 25% of the singlet state, we cannot expect any line intensity enhancement, regardless of any spin manipulations performed.

Notice that no transitions connect the singlet to the triplet state. The population of the singlet state is thus trapped, and, consequently, p-H_2 is NMR silent. Moreover, we can calculate the intensity of the global NMR signal in the two cases—that is, in the A_2 system and in the AX system. This can be done by evaluating the square of the quantities $\langle\psi|I_+^A + I_+^{A'}|\phi\rangle$

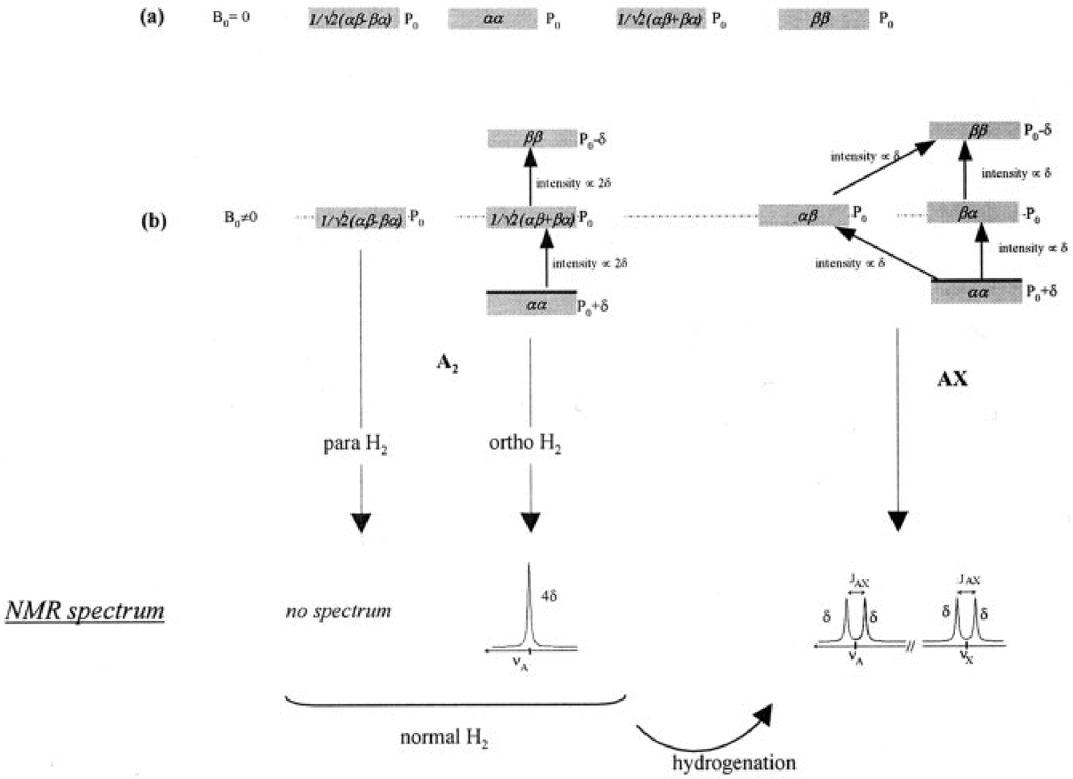

Figure 1 (a) Sketch of the energy level populations in an A_2 spin system in the absence of any static magnetic field. (b) Energy level populations in the presence of a magnetic field. Left: The A_2 spin system; right: an AX spin system resulting from a hydrogenation reaction making use of the two hydrogen atoms of the initial A_2 system. δ is the population excess of the lowest energy level in the normal hydrogen; it obeys the Boltzmann distribution and is schematized by the solid line in the lowest energy level.

or $\langle\psi|I_+^A + I_+^X|\phi\rangle$, multiplied by the difference in populations between the lower and upper states connected by a given transition, ψ and ϕ representing the relevant wave functions. This leads to 4δ for the AX system (δ/P_0 is of the order of $8\ 10^{-5}$ at ambient temperature for a proton resonance frequency of 500 MHz), whereas for the A_2 system, one has to calculate $\delta[\langle\alpha\alpha|I_+^A + I_+^{A'}|(1/\sqrt{2})(\alpha\beta + \beta\alpha)\rangle^2 + \langle(1/\sqrt{2})(\alpha\beta + \beta\alpha)|I_+^A + I_+^{A'}|\beta\beta\rangle^2]$. Again, we find 4δ, meaning that nothing is lost despite that no transition connects the singlet state.

Consider now that the para state has been enriched (at low temperature by appropriate procedures, see above) so that the population of the singlet state is $P_0 + \Delta$, the rate of enrichment being $r = \Delta/P_0$ $(0 < r \leq 3)$, that is, $r = 3$ at 0 K, whereas $r = 1$ at liquid nitrogen temperature. Δ is thus the excess in population (with respect to P_0) of the singlet state population at ambient temperature (i.e., just after the p-H_2 enrichment process and before the hydrogenation reaction). Hence the population of each level of the triplet state becomes $P_0 - \Delta/3$ and the above diagrams have to be changed accordingly. This leads to Fig. 2(a) for the situation where no static magnetic field is applied, to be compared with Fig. 1(a). In the presence of a static magnetic field (see Fig. 2, left, to be compared with Fig. 1, left), it is clear that the singlet state is now overpopulated, the amount of overpopulation depending on the enrichment rate. However, it appears impossible to extract (and take advantage) of this overpopulation as long as the two protons remain in an A_2 system, simply because no transition flows from the singlet state (see Fig. 2, left). Conversely, when an AX system is formed by means of a hydrogenation reaction inside the spectrometer magnetic field (PASADENA experiment), the αβ and βα states benefit from overpopulation, which becomes hyperpolarization (see Fig. 2, right). We know that after hydrogenation and after having placed the sample in the static magnetic field, the density operator is $K'(\hat{E}/4 - \hat{I}_z^A\hat{I}_z^X)$. From Eq. [6], it is clear that the two levels corresponding to the αβ and βα states have to be equally populated. This is the major result of density matrix calculations. Moreover, as the sum of populations of the zero spin states (i.e., $(1/\sqrt{2})(\alpha\beta - \beta\alpha)$ and $(1/\sqrt{2})(\alpha\beta + \beta\alpha)$) is conserved

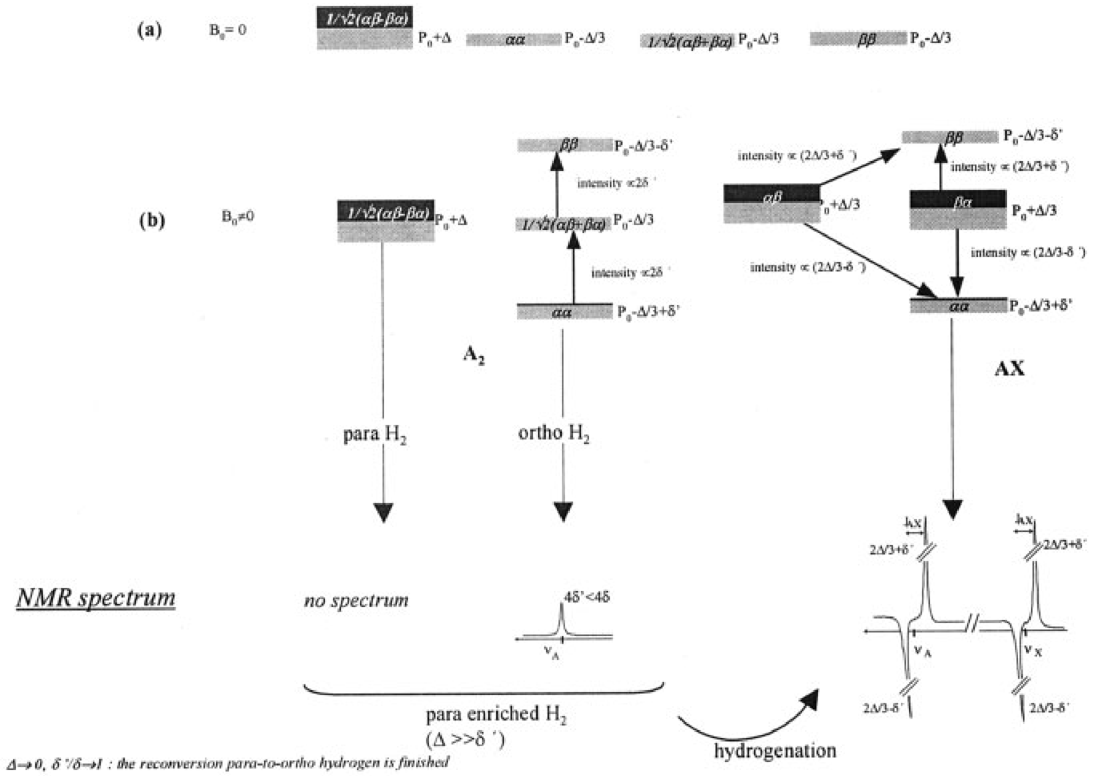

Figure 2 (a) Sketch of the energy level populations in an A_2 spin system after enrichment of the para state (denoted by Δ) in the absence of any static magnetic field. (b) Energy level populations with enrichment of the para state and in the presence of a static magnetic field. Left: the A_2 spin system; right: an AX system resulting from a hydrogenation reaction making use of the two hydrogens of the initial A_2 system. δ′ is the population excess of the lowest energy level in the para-enriched hydrogen and is schematized by the solid line in the lowest energy level. δ′/ δ is in the ratio $(P_0 - \Delta/3)/P_0$.

when going from the A_2 to the AX system by hydrogenation, we end up with $P_0 + \Delta/3$ for the population of each of these two states.

From Fig. 2(b), right, it can be seen that the enhancement of all lines is in the ratio 2 $\Delta/3\delta'$, which can be of the order of 10^4: the enhancement that is thus obtained has been widely applied to the study of hydrogenation mechanisms, and very low abundant species, such as reaction intermediates, become observable by means of parahydrogen (*9*, *32–37*) . The lines (with enhanced intensities) corresponding to transitions starting from αα will appear in emission, whereas for transitions reaching ββ, enhanced lines appear in absorption. As a result, antiphase doublets are anticipated (see next section).

EFFECT OF RADIO-FREQUENCY PULSES

To observe the intensity of the enhanced transitions mentioned in the previous section, an NMR experiment is necessary. It is well known that the effect of a radio-frequency (rf) pulse (applied, say along the *x* axis of the rotating frame) is to rotate the nuclear magnetization or, in the case of a multispin system, to rotate the operators used for the description of the states of this system (*10*). For instance, if the pulse length is adjusted to produce a rotation by an angle θ (flip angle) around the *x* axis of the rotating frame, I_z is transformed in the following way:

$$I_z \xrightarrow{(\theta)_x} I_z\cos\theta + I_y\sin\theta \qquad [9]$$

Recall that the observable quantities involve only one operator of the type I_x or I_y (to induce a signal in the detection coil). In the case of a PASADENA experiment, the state of the system, prior to the application of the rf pulse, is represented by $K'(E/4 - I_z^A I_z^X)$ and is transformed as

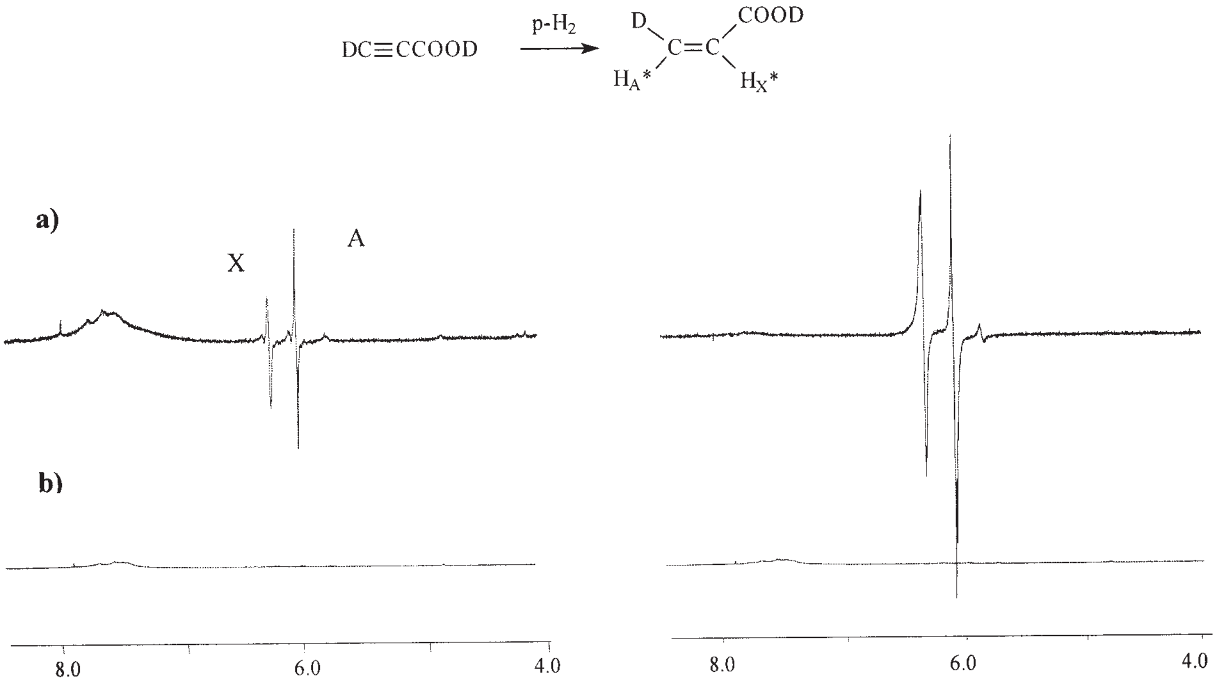

Figure 3 ^{1}H-NMR spectrum (one scan, 400 MHz) of parahydrogenated propiolic acid-d$_2$ (hydrogenation catalyst [Rh(COD)dppb]$^+$BF$_4^-$) acquired in PASADENA (left) and ALTADENA (right) experiments. The two protons of the hydrogenation product come from para-H$_2$, and an AX system is formed: the strong intensification due to nonequilibrium population of spin levels is observed comparing (a), acquired a few seconds after hydrogen addition, and (b), after the complete relaxation of the system. The longitudinal two spin order term $I_z^A I_z^X$ leads to two antiphase signals.

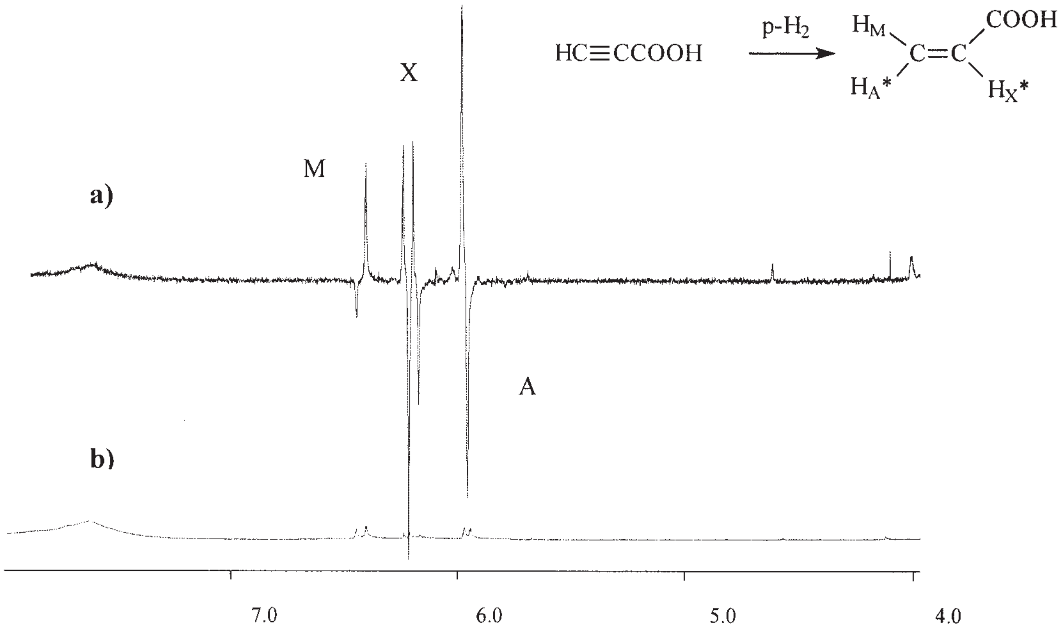

Figure 4 ^{1}H-NMR spectrum (one scan, 600 MHz) of parahydrogenated propiolic acid acquired with an ALTADENA experiment (a) acquired a few seconds after hydrogen addition and (b) after the complete relaxation of the system. The third proton that belongs to this substrate is also hyperpolarized.

$$K'(E/4 - I_z^A I_z^X) \xrightarrow{(\theta)_x} K'E/4 - K'[I_z^A I_z^X \cos^2\theta + I_y^A I_y^X \sin^2\theta + \sin\theta\cos\theta\,(I_y^A I_z^X + I_z^A I_y^X)] \quad [10]$$

$E/4$, $I_z^A I_z^X$, $I_y^A I_y^X$ do not yield any signal, whereas $I_y^A I_z^X$ and $I_z^A I_y^X$ represent observable antiphase doublets centered respectively on A and X resonance frequencies (Fig. 3, left). These are the observable quantities that benefit from the enhancement factor K'. In our case, $K' = \Delta/3$ (see above). It can be stressed that a $\pi/2$ pulse would result in no detectable signal, whereas the maximum is observed with a $\pi/4$ pulse. For an ALTADENA experiment (see Fig. 3, right), although the same formalism as above is still applies, some complications may occur. They arise from conversion of longitudinal spin order into polarization and lead to antiphase doublets with unequal intensities.

CONCLUSION

The first point to stress is that hyperpolarization (hence a considerable sensitivity enhancement) requires an enrichment in the para isomer. Because this isomer is associated with the singlet state of an A_2 spin system, it must subsequently be transformed into a spin system where the two protons are no longer magnetically equivalent.

The second point concerns the transfer of this overpopulation and the way to take advantage of it. This is described by Eq. [7], written in this case for a two-spin system. For such a spin system, the effect of hyperpolarization is tremendous, as illustrated in Fig. 3.

If the two protons of para-enriched hydrogen are inserted in a more complicated spin system, an equation similar to [7] but with the appropriate Hamiltonian can still be used. In that case, transfers toward other nuclei may occur and their amount can be predicted precisely from that equation. Figure 4 exhibits such remote transfers.

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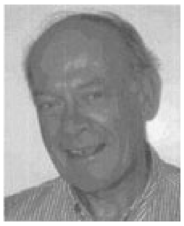
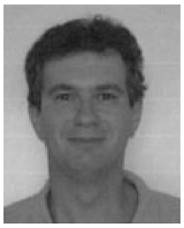
BIOGRAPHIES



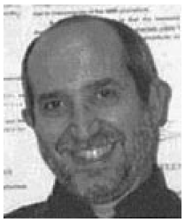
Daniel Canet was born in 1944. He earned his B.S. in 1966 and completed his thesis in 1973 at the University of Nancy, France. He has held a faculty position in this university since 1973. His research specialities are spin relaxation, radio-frequency field gradients in NMR (imaging, diffusion, and spectroscopy), and, more recently, nuclear quadrupole resonance.

Christie Aroulanda was born in 1974. She obtained her B.S. in physical chemistry in 1997 at the University Paris VII (France). In 1998, she passed the contest of Agrégation in chemistry and continued her doctoral studies at the University Paris-Sud in Orsay (France). She completed her Ph.D. in 2002 in the field of NMR spectroscopy in chiral liquid crystals. Afterward, she spent a 1-year postdoctoral training at the University of Calabria (Italy) predicting the ordering of solutes in liquid crystals using NMR spectra calculations and a Monte Carlo-type solute-solvent interactions model. She now holds a faculty position in the group of Méthodologie RMN at the University of Nancy (France).



Pierre Mutzenhardt is currently a professor of physical chemistry at the University of Nancy (France). He obtained a B.S. in physical chemistry (1988), an M.S. in theoretical chemistry (1990), and a Ph.D. on signal processing and application of radio-frequency field gradients in NMR spectroscopy (1993). He took a short postdoctoral training at the National High Magnetic Field Laboratory at Tallahassee (USA). Dr. Mutzenhardt's current interests are nuclear spin relaxation and dynamic phenomena.

Silvio Aime was born in 1948 near Torino, Italy. He received the Laurea degree in biology from the University of Torino in 1971. Following a postdoctoral appointment at the University of East Anglia (with R.K. Harris), he returned in 1974 to Torino where he has spent his entire career. He is currently professor of general and inorganic chemistry at the Faculty of Sciences (degree course in biotechnology). He is head of the NMR laboratory at the chemistry department of the University of Torino and of the Center of Excellence on Molecular Imaging (approved by MUIR in 2001).



Roberto Gobetto was born in 1956. He completed his thesis in 1980 at the University of Torino. He has held a faculty position at the same university since 1983 where he is currently a professor of inorganic chemistry. His main research interests include the synthesis, the reactivity and the characterization of metal complexes, solution and solid-state NMR studies, and the use of para hydrogen in the elucidation of hydrogenation reaction mechanisms.

Francesca Reineri was born in 1975. She received her degree in chemistry at the University of Torino in 1999 where she continued her doctoral studies in the field of hyperpolarization. She obtained her Ph.D. in 2002 with a thesis titled "NMR Studies of Hyperpolarized Gases." Then she completed 2 years of postdoctoral studies concerning the application of parahydrogen to MRI. She currently holds a research grant in the NMR laboratory of the chemistry department at the University of Torino.