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# Singlet to triplet conversion in molecular hydrogen and its role in parahydrogen induced polarization†

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Detailed experimental and comprehensive theoretical analysis of singlet–triplet conversion in molecular hydrogen dissolved in a solution together with organometallic complexes used in experiments with parahydrogen (the H<sub>2</sub> molecule in its nuclear singlet spin state) is reported. We demonstrate that this conversion, which gives rise to formation of orthohydrogen (the H<sub>2</sub> molecule in its nuclear triplet spin state), is a remarkably efficient process that strongly reduces the resulting NMR (nuclear magnetic resonance) signal enhancement, here of <sup>15</sup>N nuclei polarized at high fields using suitable NMR pulse sequences. We make use of a simple improvement of traditional pulse sequences, utilizing a single pulse on the proton channel that gives rise to an additional strong increase of the signal. Furthermore, analysis of the enhancement as a function of the pulse length allows one to estimate the actual population of the spin states of H<sub>2</sub>. We are also able to demonstrate that the spin conversion process in H<sub>2</sub> is strongly affected by the concentration of <sup>15</sup>N nuclei. This observation allows us to explain the dependence of the <sup>15</sup>N signal enhancement on the abundance of <sup>15</sup>N isotopes.

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## Introduction

Parahydrogen Induced Polarization (PHIP)<sup>1–5</sup> is a well-established low-cost tool to significantly enhance intrinsically weak NMR signals. PHIP makes efficient use of the spin order of parahydrogen (*p*H<sub>2</sub>, the H<sub>2</sub> molecule in its nuclear singlet spin state) which is converted into observable NMR signals. The possibility to enrich the *p*H<sub>2</sub> component of hydrogen gas arises from the Pauli principle which dictates the total wave function of fermions to be antisymmetric under exchange. This couples the singlet (parahydrogen) and triplet (orthohydrogen) spin states of H<sub>2</sub> with even numbered and odd numbered rotational states respectively. As a result, cooling down hydrogen gas in the presence of a catalyst to low temperatures where only the rotational ground state is populated allows to produce hydrogen gas where all molecules are in the singlet state. Once formed and removed from the interconversion catalyst parahydrogen is relatively stable to spin-reequilibration. However, since *p*H<sub>2</sub> itself is NMR silent (as it has the zero magnetic moment) a suitable chemical processes must

be harnessed to convert the spin order into an enhanced NMR signal. Such processes are given by catalytic hydrogenation reactions<sup>3</sup> with *p*H<sub>2</sub> or by reversible interactions of *p*H<sub>2</sub> with an organometallic complex.<sup>5,6</sup> In the first method, hydrogenative PHIP, *p*H<sub>2</sub> is added to a substrate with an unsaturated C–C bond; when the “nascent” protons in the reaction product stemming from *p*H<sub>2</sub> are non-equivalent (chemically or magnetically), one can obtain strong NMR signal enhancements. In the second method, termed Signal Amplification By Reversible Exchange (SABRE), *p*H<sub>2</sub> and a to-be-polarized substrate bind to an Ir-based complex, where spin order transfer gives rise to polarization of the substrate. An advantage of the SABRE method is that the substrate and *p*H<sub>2</sub> only bind to the complex transiently, *i.e.*, they are not consumed, and dissociation of substrate from the complex results in the formation of hyperpolarized free substrate molecules in solution. Hence, the substrate can be re-polarized multiple times by supplying *p*H<sub>2</sub> to the solution. The SABRE method can be used to enhance NMR signals of protons,<sup>6,7</sup> and “insensitive” nuclei such as <sup>15</sup>N and <sup>13</sup>C<sup>8–15</sup> and to polarize various molecules, notably, biomolecules,<sup>16–18</sup> metabolites,<sup>19</sup> oligopeptides,<sup>20</sup> and drugs.<sup>21–23</sup> The possibility to continuously repeat SABRE measurements with high level of reproducibility opens great perspectives for mixture analysis<sup>24</sup> and reaction monitoring<sup>25</sup> by means of SABRE.

Both hydrogenative PHIP and SABRE have been successfully applied to hyperpolarize various compounds; however, the optimization of hyperpolarization experiments still remains

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challenging. Specifically, reaction conditions have to be optimized, as well as polarization transfer efficiency. In this work, we address one more issue, which turns out to be important in both PHIP and SABRE. Specifically, we address the question: "What is the spin order of  $H_2$  in PHIP/SABRE experiments?". At the first glance, this question seems to make no sense, as we always introduce  $pH_2$ , i.e., two protons in the nuclear singlet spin state, into the chemical reaction. However, this obvious answer holds only in the gas phase, where conversion between  $pH_2$  and triplet  $H_2$  (orthohydrogen,  $oH_2$ ) is a very slow process. For the actual PHIP and SABRE processes the answer is not so obvious because  $pH_2$  binds to a PHIP substrate or SABRE catalyst in such a way that the two protons occupy non-equivalent positions. In this situation, their magnetic or chemical equivalence is broken and singlet-triplet conversion in  $H_2$  becomes operative. It is important to note that the conversion is not equivalent to a simple decay of singlet spin order *via* relaxation, since hyperpolarized  $oH_2$  can be formed in a strongly non-equilibrium state, as has been confirmed by several groups.<sup>26–28</sup>

The aim of this work is to study in detail spin conversion of  $H_2$  and to characterize its actual spin state. Here we perform the study for a SABRE system (using an Ir-based catalyst) and measure the SABRE-derived enhancement of  $^{15}N$  spins. By introducing radio-frequency pulses on the proton channel (which have no effect  $pH_2$  since it is in a rotation-invariant singlet state, but modify the state of  $oH_2$ ) we are able to probe the amount of  $pH_2$  and to determine the state of non-thermally polarized  $oH_2$ . Furthermore, we reveal the influence of the magnetic  $^{15}N$  isotope on the singlet-triplet conversion in complex-bound  $H_2$ . This effect is conditioned by a weak symmetry breaking resulting in magnetic non-equivalence of the chemically equivalent  $pH_2$ -nascent protons in the SABRE complex. The study presented here is driven not only by general interest and curiosity, but has important practical consequences for optimizing PHIP and SABRE experiments and for achieving the highest possible NMR signal enhancement. There are two reasons for this. First, the lifetime of the spin order of  $H_2$  (which is the source of NMR signal enhancement) is important to achieving maximal polarization. Second, some of the pulse sequences for transferring spin order from  $H_2$  have been designed assuming that the initial spin order of the two protons is a pure state of singlet order: such pulse sequences might become inefficient when the spin state of  $H_2$  is a mixture of  $pH_2$  and  $oH_2$ . We clearly show in this work that the formation of hyperpolarized  $oH_2$  is an important factor in PHIP and SABRE, which has a strong influence on the resulting NMR signal enhancement.

## Methods

### Sample preparation

All experiments presented here were done for a SABRE system using the  $IrCl(COD)(IMes)$  complex,<sup>29</sup> where  $IMes$  = 1,3-bis(2,4,6-trimethylphenyl)imidazole-2-ylidene and  $COD$  = cyclooctadiene;

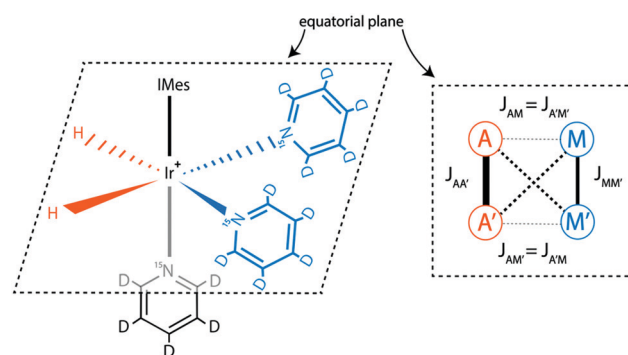
activation of this pre-catalyst by hydrogenation of  $COD$  and addition of pyridine forms the main dihydride Iridium complex  $[Ir(H)_2(IMes)(Py)_3]^+$ , with  $Cl^-$  as a counter ion ( $Py$  = pyridine). The structure of the SABRE complex is given in Fig. 1. The SABRE process in this system is due to exchange of  $H_2$  and  $Py$  between their free forms in solution and bound forms. It is important to note that in methanol solution there is also exchange<sup>30</sup> between the main complex and two other complexes: one with a  $Cl^-$  and one with an equatorial  $Py$  ligand replaced by a methanol solvent molecule. In these complexes the  $pH_2$ -nascent protons are chemically non-equivalent, which strongly affects<sup>30</sup> the spin conversion. To simplify the reacting system, we have replaced the  $Cl^-$  counter-ion with  $PF_6^-$ , which does not bind to the complex. As previously described<sup>30</sup> this can be achieved by adding  $AgPF_6$  and removing the resulting  $AgCl$  precipitate from the sample. As a SABRE substrate, we used either  $^{15}N$ -labelled  $Py-d_5$  or mixtures of  $^{15}N$ - $Py-d_5$  and  $^{14}N$ - $Py-d_5$ , thus varying the abundance of the spin-1/2  $^{15}N$  isotopes. Using a deuterated substrate allowed to simplify the spin system and, hence, to ease the optimization and interpretation of SABRE experiments. In all experiments the sample temperature was 25 °C.

The spin system of the main SABRE complex can be modelled as an  $AA'MM'$  system, as shown in Fig. 1. Here the A-spins stand for the protons originating from  $pH_2$ , while the M-spins are the  $^{15}N$  nuclei of the two equatorial  $Py$  ligands.

### NMR experiments

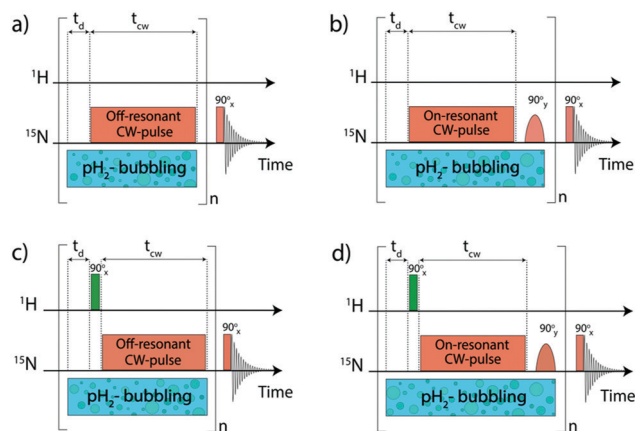
NMR experiments were mostly carried out at high magnetic fields using the protocols shown in Fig. 2. To polarize the  $^{15}N$  nuclei we used pulse sequences with radiofrequency (rf) pulses applied to the  $^{15}N$  channel. For transferring spin order from  $pH_2$  essentially a single long  $^{15}N$  pulse of a low intensity is used, hereafter called pseudo continuous-wave ("pseudo cw") pulse.

When the parameters of the rf field applied to the  $^{15}N$  channel are properly set, proton singlet spin order is transferred to  $^{15}N$  spins in the SABRE complex. Specifically, the



**Fig. 1** Structure of the iridium SBRE complex; molecular hydrogen and the substrate (with two  $Py$  ligands in equatorial positions, and a third  $Py$  in an axial position) are indicated. The spin system of the SABRE complex is also shown, here modelled as an  $AA'MM'$  system (A-spins stand for the  $pH_2$  protons and M-spins belong to the  $^{15}N$  nuclei of the two equatorial  $Py$  ligands).





**Fig. 2** Experimental protocols used to run high-field SABRE experiments, aimed at enhancing  $^{15}\text{N}$  signals of free Py in solution.  $\text{pH}_2$  is supplied to the sample using an automated bubbling device. The pseudo cw pulse on the  $^{15}\text{N}$  channel is applied either exactly on resonance of the complex bound Py (b and d) or slightly off-resonance (a and c); in the former case an additional  $90^\circ$  pulse is used to generate the longitudinal polarization. In (a and b) no pulses are applied on the proton channel, whereas in (c and d)  $90^\circ$  pulses on the proton channel are used. After each cycle Py-ligands bound to the Ir complex are polarized; this polarization is transferred to free Py in solution *via* ligand exchange. The polarization cycle is repeated  $n$  times and the  $^{15}\text{N}$  NMR signal is acquired after applying a  $90^\circ$  pulse. The delay between the cycles is equal to  $t_d$  and the duration of the  $^{15}\text{N}$  pseudo cw pulse is denoted as  $t_{\text{cw}}$ .

effective field  $\omega_{\text{eff}}$  (given in the frequency units) should be matched<sup>9,31,32</sup> to a certain combination of scalar  $J$ -couplings in the  $\text{AA}'\text{MM}'$  system. The effective field is given by the vector sum of the transverse rf-field (in the rf-rotating frame) and the longitudinal field given by offset from resonance  $\omega_{\text{eff}} = \sqrt{\omega_1^2 + \Delta^2}$  where  $\omega_1$  is the rf-field strength and  $\Delta$  the resonance offset. A more detailed discussion of the definition of  $\Delta$  for the system under study is given below. In the case of single-resonance experiments (excitation only on the  $^{15}\text{N}$  channel) the source of polarization is given by the population difference of the singlet and central triplet states of  $\text{H}_2$ . As we show below, this feature is critical for the performance of the pulse sequences.

The magnetization transferred to the  $^{15}\text{N}$  nuclei is parallel to the effective field. Hence, it is a purely transverse magnetization when  $\Delta = 0$  (on-resonance excitation); whereas for  $\Delta \neq 0$  the magnetization has a longitudinal component. In SABRE, one seeks to generate polarization of the free substrate molecule *via* chemical exchange. Upon exchange, longitudinal polarization of the bound species is transferred to the free substrate pool. Thus, in the case of resonant excitation, an additional  $90^\circ$  pulse should be inserted to convert transverse into longitudinal polarization; when  $\Delta \neq 0$  this may be not necessary. To maximize  $^{15}\text{N}$  signal enhancement, the polarization transfer cycle is repeated  $n$  times.<sup>31</sup> For this reason, the additional  $90^\circ$  pulse should be selective, exciting only the bound substrate, but not its free form in solution. Finally, after applying a  $90^\circ$  pulse, the  $^{15}\text{N}$  Free Induction Decay (FID) signal is acquired (its Fourier transform gives the NMR spectrum). Two of the pulse sequences shown in Fig. 2 exploit resonant rf-excitation (Fig. 2b and d), whereas the

other two make use of off-resonant excitation (Fig. 2a and c). The sequence in Fig. 2b is known as LIGHT-SABRE (Low-Irradiation Generation of High Tesla-SABRE).<sup>31</sup>

Two of the pulse sequences (Fig. 2c and d) in Fig. 2 comprise a modification which would be meaningless if we were dealing only with pure rotation-invariant singlet order: this is a  $90^\circ$  pulse applied to the proton channel. It turns out that this pulse strongly affects the performance of the polarization transfer experiment if some hyperpolarized  $\text{oH}_2$  is generated. In this work, we analyse the effect of proton pulses with arbitrary nutation angles on the  $^{15}\text{N}$  NMR signal enhancement. The pulse sequences given in Fig. 2c and d are known<sup>9</sup> as SLIC-SABRE (Spin-Locking Induced Crossing SABRE<sup>33</sup>).

In addition to high-field NMR experiments, we also performed field-cycling NMR studies, in which polarization was allowed to build up by SABRE at an ultralow magnetic field (in the range  $10 \text{ nT} < B_0 < 1 \mu\text{T}$ ). Subsequently the hyperpolarized sample is transferred to an 400 MHz NMR spectrometer ( $B_0 = 9.4 \text{ T}$ ). To run such experiments, we used a home-built device for sample shuttling with a set of coils inside the magnetic shield, as described before.<sup>11,34</sup>

All NMR spectra were recorded using a 400 MHz Bruker NMR spectrometer. In all high-field SABRE experiments the *para*-component of  $\text{H}_2$  was enriched to 85% by using a commercial Bruker parahydrogen generator. In ultralow field experiments we have used 95% enriched  $\text{pH}_2$ , obtained by cooling down  $\text{H}_2$  in a helium cryostat CFA-200-H2CELL (Cryo-Pribo). The  $\text{pH}_2$  bubbling pressure was equal to 2 bar. The signal enhancement factor  $\varepsilon$  (ratio of the hyperpolarized  $^{15}\text{N}$  NMR signal and thermal signal both measured at 9.4 tesla) gives a measure of polarization.

## Results and discussion

### Theoretical analysis of singlet-triplet conversion

To analyse singlet-triplet conversion in  $\text{H}_2$  and to optimize the pulse sequences we used spin dynamics simulations and additionally took into account exchange of  $\text{H}_2$  or SABRE substrate.

In order to consider spin conversion in molecular hydrogen, we introduce a set of equations for the spin density operators,  $\sigma_f$  and  $\sigma_b$ , of free and bound  $\text{H}_2$ , respectively:

$$\begin{cases} \frac{d}{dt} \sigma_f = -i[\hat{H}_f, \sigma_f] - \hat{I}_f \sigma_f - k_{\text{as}} \sigma_f + k_{\text{dis}} \sigma_b \\ \frac{d}{dt} \sigma_b = -i[\hat{H}_b, \sigma_b] - \hat{I}_b \sigma_b - k_{\text{dis}} \sigma_b + k_{\text{as}} \sigma_f \end{cases}$$

Here  $\hat{H}_{f,b}$  stand for the Hamiltonians of the free or bound  $\text{H}_2$  (all Hamiltonians are given in  $\hbar$  units);  $\hat{I}_{f,b}$  are the corresponding relaxation superoperators;  $k_{\text{as}}$  is the rate of association of  $\text{H}_2$  to form the Ir-based complex and  $k_{\text{dis}}$  is the dissociation rate of molecular hydrogen from the complex. Here, we choose the normalization  $\text{Tr}\{\sigma_f\} + \text{Tr}\{\sigma_b\} = 1$ . In this case, the *total* probability of finding  $\text{H}_2$  either in the free form ( $\sigma_f$ ) or in the bound form ( $\sigma_b$ ) is equal to unity, but not their individual



traces.<sup>35</sup> This model is sufficient to simulate singlet-triplet conversion, which gives rise to hyperpolarized  $\text{oH}_2$ . To carry out these simulations, we introduce  $\hat{H}_{\text{f,b}}$  in the rotating frame (this is done to ease numerical calculations and to get rid of the large nuclear Zeeman interaction with the  $B_0$  field, which is parallel to the  $z$ -axis). For simplicity, we take the frequency of the rotating frame equal to the NMR frequency of free  $\text{H}_2$ , so that  $\hat{H}_{\text{f}} = 0$  and  $\hat{H}_{\text{b}} = \Omega_1 \hat{I}_{1z} + \Omega_2 \hat{I}_{2z}$  (here  $\hat{I}_1$  and  $\hat{I}_2$  are the spin operators of the two non-equivalent bound protons,  $\Omega_{1,2}$  are their NMR frequencies in the rotating frame). In fact, the only relevant parameter in  $\hat{H}_{\text{b}}$  is the frequency difference  $\delta\omega = |\Omega_1 - \Omega_2|$ . Indeed, it is the term

$$\frac{1}{2} \delta\omega \{\hat{I}_{1z} - \hat{I}_{2z}\}$$

which is responsible for driving the transitions between the singlet state  $|S\rangle$  and central triplet state  $|T_0\rangle$ , as illustrated by the vector diagram<sup>36</sup> in Fig. 3. Setting  $\delta\omega \neq 0$  we assume that the chemical equivalence of the two protons in the complex is broken, giving rise to a non-vanishing difference in their chemical shifts. Alternatively, symmetry breaking can be due to magnetic non-equivalence, *i.e.*, caused by a difference in  $J$ -couplings with other spin-1/2 nuclei present in the complex. In both cases we achieve  $\delta\omega \neq 0$ . The singlet-triplet states are introduced in the usual way:

$$|S\rangle = \frac{1}{\sqrt{2}}\{|\alpha\beta\rangle - |\beta\alpha\rangle\}, \quad |T_0\rangle = \frac{1}{\sqrt{2}}\{|\alpha\beta\rangle + |\beta\alpha\rangle\}$$

$$|T_+\rangle = |\alpha\alpha\rangle, \quad |T_-\rangle = |\beta\beta\rangle$$

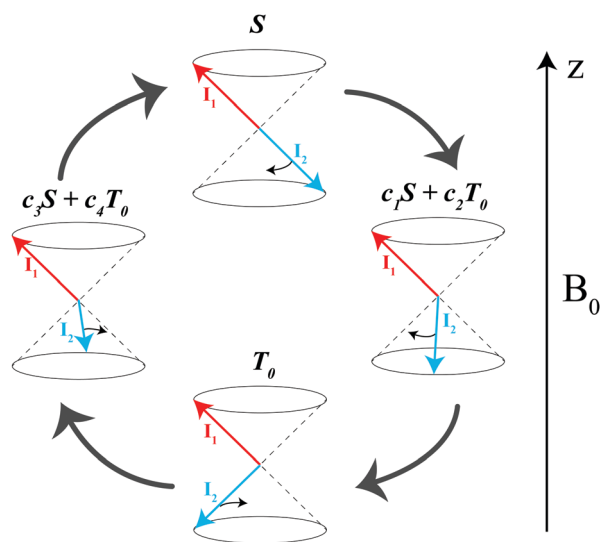


Fig. 3 Diagram explaining singlet-triplet conversion for  $\delta\omega \neq 0$ . The arrows stand for the spin vectors of the two protons, the  $|S\rangle$  state is the state with anti-parallel spins while in the  $|T_0\rangle$  state the total spin is non-zero but its  $z$ -projection is zero. The spins precess about the  $B_0$  field at different frequencies: faster precession of one of the spins (for simplicity, we assume that only  $I_2$  precesses) gives rise to coherent  $S \rightarrow T_0$  mixing, *i.e.*,  $|S\rangle$  goes to a superposition of  $|S\rangle$  and  $|T_0\rangle$ , then to  $|T_0\rangle$ , then again to a superposition and so on.

where  $|\alpha\rangle$  and  $|\beta\rangle$  are the states of a spin-1/2 particle with  $z$ -projections equal to  $+\frac{1}{2}$  and  $-\frac{1}{2}$ , respectively.

As far as relaxation effects are concerned, we merely consider the simplest case of relaxation driven by fluctuating local fields experienced by the two protons, ignoring the fluctuations of their mutual dipole-dipole coupling. We also assume that the local fields are almost completely correlated, which implies that they efficiently drive the transitions between the triplet states, but not the transitions between the singlet state and triplet states. Hence, in the absence of exchange, singlet-triplet conversion takes infinitely long (in experiments, conversion in the absence of a SABRE catalyst is indeed a very slow process). Precise details and parameters of the model are given in ESI,<sup>†</sup> as well as the method for numerical solution of the set of equations.

According to the model outlined above, singlet-triplet conversion in  $\text{H}_2$  occurs in the following way. When  $\text{H}_2$  binds to the complex, the chemical equivalence is lifted so that coherent transitions between the  $|S\rangle$  and the central  $|T_0\rangle$  states become operative. As a result, the population is distributed between these two states. This gives rise to formation of  $\text{oH}_2$  in a non-equilibrium spin state. Subsequently, spin relaxation comes into play and tends to equalize the populations of the three triplet states; eventually, all four states acquire the same population. The rate of the first conversion step  $S \rightarrow T_0$  critically depends on  $\delta\omega$ ,  $k_{\text{as}}$  and  $k_{\text{dis}}$ . Simulations assuming an initial  $|S\rangle$  state of  $\text{H}_2$  are shown in Fig. 4 for different  $\delta\omega$  values, presenting the time dependence of the populations of the  $|S\rangle$ ,  $|T_0\rangle$  and  $|T_{\pm}\rangle$  states, and of the population imbalance  $\delta P = P_S - P_{T_0}$ . When  $\delta\omega$  is small, the conversion process is very slow (just like the inefficient singlet-triplet relaxation in free  $\text{H}_2$ ). As  $\delta\omega$  increases, the populations of the  $|S\rangle$  and  $|T_0\rangle$  states are redistributed in a coherent fashion *via* spin mixing in the complex and  $P_{T_0} \neq 0$ . As the central  $|T_0\rangle$  state gets populated, relaxation between the triplet states also populates the  $|T_{\pm}\rangle$  states,  $P_{T_{\pm}} \neq 0$ . Hence, spin order conversion is a two-step process. With the parameters chosen in Fig. 3, the  $|S\rangle$  and  $|T_0\rangle$  state populations are rapidly equilibrated and  $\delta P \rightarrow 0$ , whereas the  $|T_0\rangle$  population remains different from that of the  $|T_{\pm}\rangle$  states for longer time. Moreover, introducing the spin-spin coupling constant between two hydrid protons  $J_{\text{HH}}$  alters the described behavior, especially for the case of moderate  $\delta\omega$  values. This coupling induces the energy splitting between the singlet and the triplet manifolds, thus decreasing the rate of  $S \rightarrow T_0$  transitions. However, when  $\delta\omega$  exceeds  $J_{\text{HH}}$ , the process of  $\delta P$  reduction is very similar to the case of  $J_{\text{HH}} = 0$ .

### Optimization of the pulse sequence

Before comparing the performance of the pulse sequences of interest, we optimized the experimental parameters, such as the delays  $t_d$  and  $t_{\text{cw}}$  and the number of cycles  $n$ . The dependence of the enhancement on these parameters is presented in ESI.<sup>†</sup> In the experiments presented below we always set  $t_d = 500$  ms,  $t_{\text{cw}} = 39$  ms and  $n = 50$ , which provide substantially improved signal enhancements.





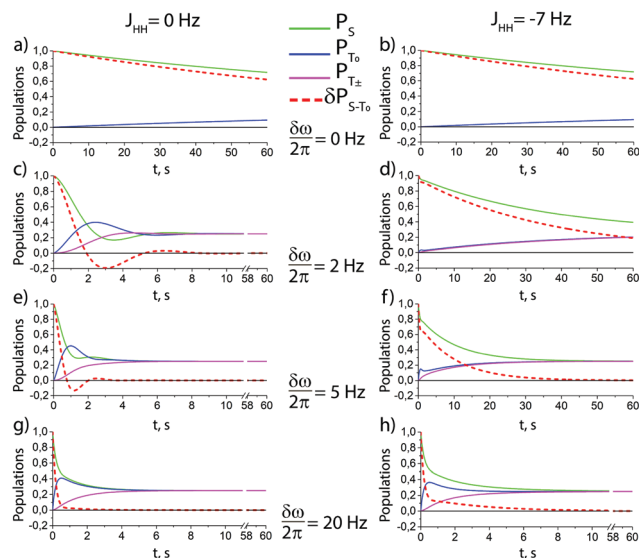


Fig. 4 Theoretical time dependence of the spin state populations of  $H_2$  and the population difference  $\delta P = P_S - P_{T_0}$  in the presence of exchange between bound and free hydrogen. Calculation parameters:  $k_{as} = 6 \text{ s}^{-1}$ ,  $k_{dis} = 60 \text{ s}^{-1}$ ,  $(T_1^{fH_2} = 3 \text{ s}, T_1^{bH_2} = 1 \text{ s})$  for all subplots; the  $\delta\omega/2\pi$  equal to 0 Hz (subplots a and b), 2 Hz (subplots c and d), 5 Hz (subplots e and f), and to 20 Hz (subplots g and h); the spin-spin coupling constant between two hydrid protons  $J_{HH} = 0 \text{ Hz}$  (left column), and  $J_{HH} = -7 \text{ Hz}$  (right column). The relaxation model considers only fluctuating local fields, experienced by the two spins, which are modelled as almost completely correlated, so that singlet-triplet relaxation transitions are slow, as compared to transitions within the triplet manifold (see ESI† for a detailed explanation).

To optimize the performance of the pulse sequence, it is necessary to set the optimum resonance offset  $\Delta$  for the pseudo cw pulse. As pointed out above, the optimization is different for a single pulse and for a pulse followed by an additional  $90^\circ$  pulse. This is indeed the case, see Fig. 5. When no extra pulses are used, the resulting longitudinal  $^{15}\text{N}$  polarization vanishes for  $\Delta = 0$  (the spins are polarized parallel to the effective field, and therefore do not have any longitudinal component). When an additional  $90^\circ$  pulse is used to convert the transverse polarization into longitudinal polarization, the resulting polarization is maximal for  $\Delta = 0$ . The  $\Delta$ -dependence of polarization shows positive and negative extrema, see Fig. 5a, corresponding to matching of the energy levels of the AA'MM' spin system in the rotating frame, as explained before.<sup>9</sup> To make the pulse sequences work one should also optimize the  $\omega_1$  value:<sup>9</sup> when  $\omega_1$  is very small, spin mixing is inefficient, whereas if  $\omega_1$  is much larger than the relevant  $J$ -couplings, the matching conditions can no longer be fulfilled (this is the reason for using a low-intensity cw rf pulse). In the experimental  $\omega_1$  dependence of the enhancement, see Fig. 5b, the peak corresponds to the matching condition.

### NMR signal enhancement

We have optimized the relevant experimental parameters for all four protocols shown in Fig. 2. One can see that using off-resonant excitation with a small  $\Delta$  value one can achieve higher  $\varepsilon$  values, see Fig. 5. Although the theoretical treatment suggests that the efficiency of the scheme should be the same or even

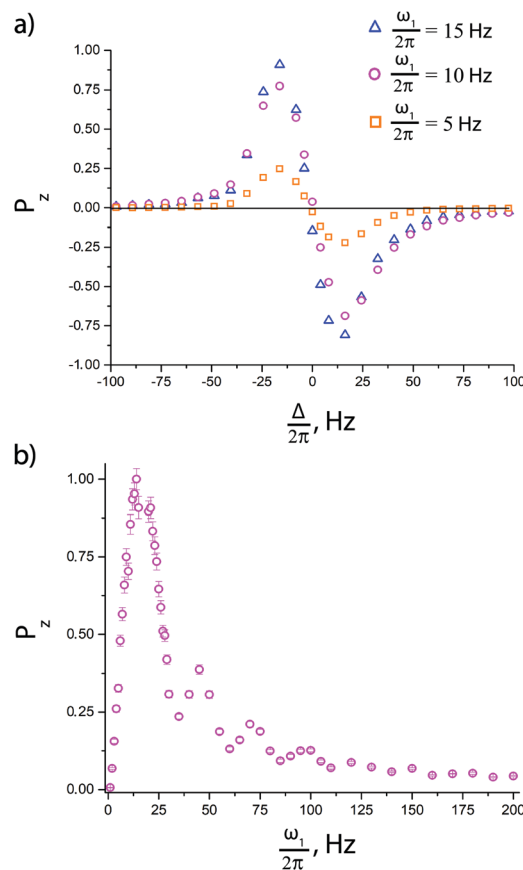


Fig. 5 (a) Dependence of  $^{15}\text{N}$  polarization in the SLIC-SABRE method on the offset  $\Delta$  shown for different  $\omega_1$  values:  $\omega_1/2\pi = 5 \text{ Hz}$  (squares),  $\omega_1/2\pi = 10 \text{ Hz}$  (circles) and  $\omega_1/2\pi = 15 \text{ Hz}$  (triangles). (b) Dependence of  $^{15}\text{N}$  polarization on the rf nutation frequency  $\omega_1$  for SLIC-SABRE with an off-resonant pulse (for  $\Delta = -14 \text{ Hz}$ ). The experiments were performed with substrate concentration  $[S] = 95 \text{ mM}$  and catalyst concentration  $[C] = 7 \text{ mM}$ ; the polarization is normalized to its maximal value in both cases.

higher for resonant excitation ( $\Delta = 0$ ); this experiment is more difficult to optimize, in particular, when chemical exchange is constantly going on, as is the case in SABRE. The enhancements obtained by these two methods are moderate,  $\varepsilon \approx 30$  for resonant excitation and  $\varepsilon \approx 150$  for off-resonant excitation, for the experimental conditions used here. We attribute this to efficient S- $T_0$  conversion, rendering  $\delta P$  small. Since this population imbalance is the source of non-thermal spin order, the signal enhancement factors become low.

A simple way to re-introduce the  $\delta P$  population imbalance is to exploit the difference in populations between the  $|T_0\rangle$  and  $|T_{\pm}\rangle$  states. This can be done in different ways.<sup>9</sup> Here we investigate the simple method of using a single  $90^\circ$  pulse on the proton channel. In this situation, the state populations change as follows (we assume that before applying the pulse  $P_{T_+} = P_{T_-} = P_{T_{\pm}}$ ):

$$P'_S = P_S, \quad P'_{T_0} = \frac{1}{2} \{P_{T_+} + P_{T_-}\} = P_{T_{\pm}},$$

$$P'_{T_{\pm}} = \frac{1}{2} P'_{T_0} + \frac{1}{4} \{P_{T_+} + P_{T_-}\} = \frac{1}{2} P_{T_0} + \frac{1}{2} P_{T_{\pm}}$$



Here the populations with primes stand for the state populations after applying the pulse. Hence, the  $P_S$  population remains the same (as the singlet state is invariant to rotations), whereas the  $P_{T_0}$  population is altered. Hence,  $\delta P$  changes from the value  $\{P_S - P_{T_0}\}$  to  $\delta P' = \{P_S - P_{T_\pm}\}$ . Assuming that S- $T_0$  conversion is considerably more efficient than S- $T_\pm$  conversion, one should expect that  $\delta P$  should increase significantly, as should the resulting enhancement.

To exploit this effect, we have run two more experiments (with on- and off-resonance excitation) using an additional  $90^\circ$  proton pulse prior to the polarization transfer sequence. As one can see from Fig. 6, the resulting enhancement dramatically increases for both transfer schemes, here approximately by a factor of 7. This is a clear indication that fast and efficient S- $T_0$  conversion in  $H_2$  is indeed taking place in the studied sample. Comparison of the pulse sequences also shows that applying a  $90^\circ$  proton pulse is indeed an efficient way to re-establish the desired S- $T_0$  population difference.

One should note that the resulting  $^{15}N$  spectra yield a broadened NMR signal with a non-Lorentzian lineshape. This is a result of exchange of deuterons in the *ortho*-positions of Py with dihydrogen protons, which leads to the formation of three isotopomers of free pyridine, with D-D, H-D and H-H nuclei in

the *ortho*-positions.<sup>10</sup> Since each isotopomer has its own spin system, the spectral pattern becomes more complex and contains several components. However, the signal of fully deuterated pyridine dominates over any other signal in the resulting  $^{15}N$  spectra,

The improvement of the enhancement  $\varepsilon$  by a factor of 7 allows one to calculate the populations of the spin states of  $H_2$ . Here we do so assuming that (i)  $\varepsilon$  is proportional to  $\delta P$  and (ii)  $P_{T_\pm} = 0.05$  (this corresponds to 85% of  $pH_2$  enrichment). Hence, if we set  $P_S = x$  before the pulse is applied, we obtain that  $P_{T_0} = 0.9 - x$ . After application of the pulse we obtain  $P'_S = P_S = x$  and  $P'_{T_0} = P_{T_\pm} = 0.05$ . Consequently,

$$\frac{\delta P'}{\delta P} = \frac{x - 0.05}{2x - 0.9} \approx 7 \Rightarrow x \approx 0.48$$

Hence, we obtain about 48% of  $H_2$  in the  $|S\rangle$  state and about 42% in the  $|T_0\rangle$  state and 10% in the  $|T_\pm\rangle$  states, *i.e.*, a relatively small population difference of about 6%. After applying the additional pulse it increases to as much as 43%.

### Singlet-triplet conversion

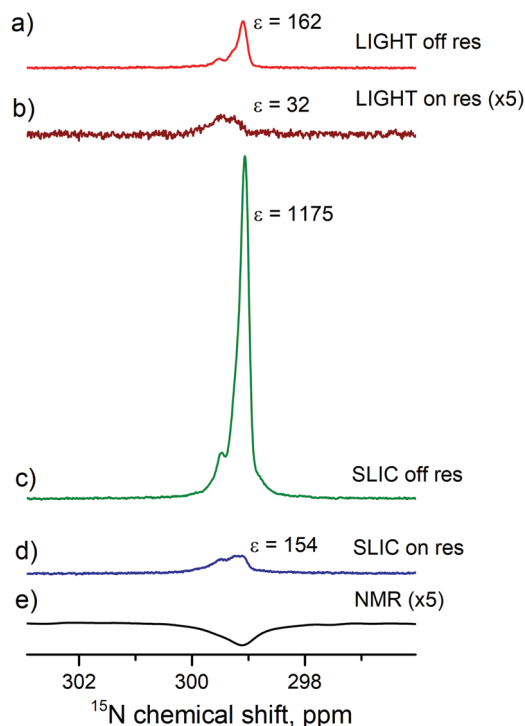
Inspired by the strong, approximately 7-fold, improvement of  $\varepsilon$  provided by the pulse applied to protons, we decided to look more closely at the singlet-triplet conversion efficiency. To this end, we have varied the length of the proton pulse and measured  $\varepsilon$  as a function of the flip angle  $\varphi$  of this pulse, see Fig. 7a. The experimental data were fitted by the periodic function  $\varepsilon(\varphi) = a_1 - a_2 \cos(2\varphi)$ , with the maxima at  $\varphi = (1/2 + m)\pi$  and the minima at  $\varphi = m\pi$  ( $m$  is an integer number). The maximal value is  $\varepsilon_{\max} = a_1 + a_2 \propto \delta P'$  and the minimal value is  $\varepsilon_{\min} = a_1 - a_2 \propto \delta P$ . The ratio

$$\frac{\varepsilon_{\max}}{\varepsilon_{\min}} = \frac{\delta P'}{\delta P}$$

thus can be used to characterize the efficiency of the S- $T_0$  conversion process, which is due to symmetry breaking in  $H_2$  bound to the SABRE complex. Symmetry breaking can be due to the chemical shift difference between the two protons and/or to subtler effects of  $J$ -couplings. In the SABRE complex, the  $^1H$ - $^{15}N$   $J$ -couplings are sizeable; furthermore, there is a large difference in the couplings  $J_{AM} = J_{A'M'}$  and  $J_{A'M} = J_{AM'}$ , so that it has been estimated that  $\delta J = J_{AM} - J_{A'M} \approx 20$  Hz. As a consequence, the two  $pH_2$ -nascent protons become magnetically non-equivalent and the effective  $\delta\omega$  value becomes non-zero.

We have studied the effect of symmetry breaking through magnetic non-equivalence by varying the enrichment of  $^{15}N$  nuclei, *i.e.*, by using a mixture of  $^{14}N$ -Py and  $^{15}N$ -Py (the fast relaxing quadrupolar  $^{14}N$  nuclei do not alter the spin dynamics of the proton system).

In Fig. 7b, the ratio  $\frac{\varepsilon_{\max}}{\varepsilon_{\min}}$  is plotted as a function of the fraction of  $^{15}N$  nuclei (we used three values,  $\eta_{^{15}N} = 10\%$ ,  $30\%$  and  $100\%$  of  $^{15}N$ -Py) and measured the dependence for two different concentrations  $[C]$  of the catalyst. We have set the total concentration of substrate (both  $^{15}N$  labelled and non-labelled) equal to 190 mM in order to achieve sufficient signal-to-noise



**Fig. 6** Comparison of the polarization transfer schemes shown in Fig. 2. LIGHT-SABRE scheme with off-resonant CW pulse followed by a selective  $90^\circ$  proton pulse (a) and on-resonant CW  $^{15}N$  pulse (b). SLIC-SABRE scheme (with an additional hard  $90^\circ$  proton pulse before polarization transfer) with off-resonant CW  $^{15}N$  pulse followed by a selective  $90^\circ$   $^{15}N$  pulse (c) and an on-resonant CW  $^{15}N$  pulse (d). Thermal signal acquired with 256 transients is presented as a reference (e). Experimental parameters:  $[S] = 95$  mM,  $[C] = 7$  mM,  $\omega_1/2\pi = 10$  Hz,  $n = 50$ ,  $t_d = 500$  ms,  $t_{cw} = 39$  ms,  $\Delta/2\pi = -14$  Hz (for off-resonant excitation).



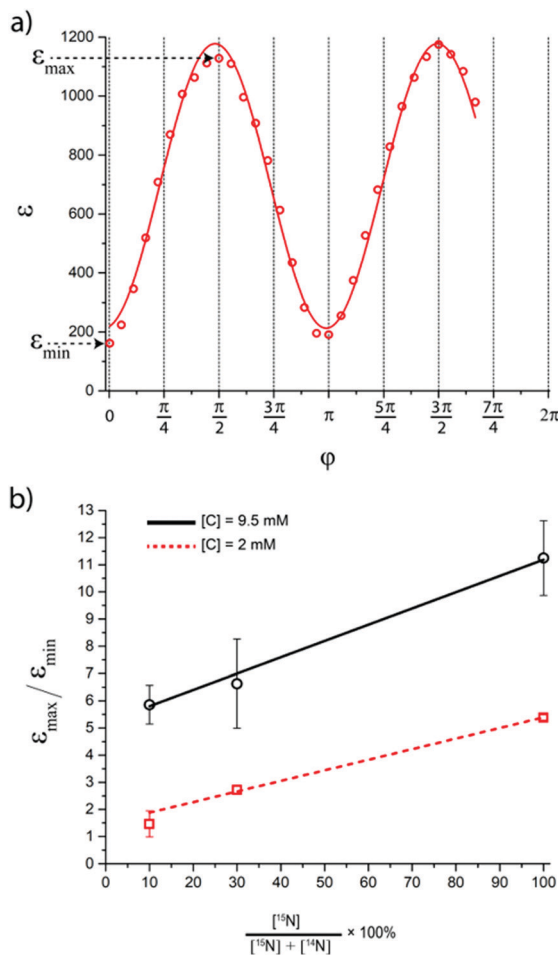


Fig. 7 (a) The dependence of  $^{15}\text{N}$  signal enhancement on the flip angle  $\phi$  of the proton pulse. The experiments were performed with  $[\text{S}] = 95 \text{ mM}$  and  $[\text{C}] = 7 \text{ mM}$ , deuterated  $^{15}\text{N}$ -enriched Py was used. Experimental parameters:  $\omega_1/2\pi = 10 \text{ Hz}$ ,  $n = 50$ ,  $t_d = 500 \text{ ms}$ ,  $t_{\text{cw}} = 39 \text{ ms}$ , offset  $\Delta/2\pi = -14 \text{ Hz}$ . (b) The dependence of  $^{15}\text{N}$  signal enhancement ratio  $\frac{\epsilon_{\text{max}}}{\epsilon_{\text{min}}}$  on the percentage of  $^{15}\text{N}$  enrichment of pyridine in the solution, measured for  $[\text{C}] = 2 \text{ mM}$  (squares) and  $9.5 \text{ mM}$  (circles).  $[\text{S}]$  is equal to  $190 \text{ mM}$  (total concentration of  $^{14}\text{N}$ -Py and  $^{15}\text{N}$ -Py); straight lines are drawn to guide the eye. We used solutions after ion exchange with  $\text{AgPF}_6$ .

ratio in cases where the SABRE signal was low, *i.e.* LIGHT-SABRE experiments with an  $^{15}\text{N}$  enrichment  $\eta_{15\text{N}}Z = 10\%$ . One can see that the effect of  $^{15}\text{N}$  spins is significant, in particular, at low  $[\text{C}]$  concentration, where the violation of magnetic equivalence of the protons in bound  $\text{H}_2$  is the dominant mechanism. Note that  $\frac{\epsilon_{\text{max}}}{\epsilon_{\text{min}}}$  increases from 1 for  $\eta_{15\text{N}} = 10\%$  to approximately 5 for  $\eta_{15\text{N}} = 100\%$ . For higher concentrations  $[\text{C}]$  other conversion mechanisms come into play as well, most likely coming from other complexes with molecular hydrogen. This follows from the fact that  $\frac{\epsilon_{\text{max}}}{\epsilon_{\text{min}}} = 5$  for  $\eta_{15\text{N}} = 10\%$ . Nonetheless, the contribution of magnetic non-equivalence to symmetry breaking is still significant in this case, as  $\frac{\epsilon_{\text{max}}}{\epsilon_{\text{min}}}$  increases by roughly a factor of 2 for  $\eta_{15\text{N}} = 100\%$ . Remarkably,  $\frac{\epsilon_{\text{max}}}{\epsilon_{\text{min}}} > 10$

at high  $[\text{C}]$  and for  $\eta_{15\text{N}} = 100\%$ . Hence, the contribution of symmetry breaking driven by scalar  $^1\text{H}$ - $^{15}\text{N}$  couplings in the SABRE complex to overall conversion is significant. Furthermore, this contribution strongly affects the resulting enhancement.

### Ultra-low field experiments

In this context, it is interesting to estimate how the resulting  $^{15}\text{N}$  enhancement depends on the abundance of  $^{15}\text{N}$  nuclei in the SABRE substrate. The experimental data shown in Fig. 7 do not give a complete and clear answer to this question: in this figure, only relative  $\epsilon$  values are presented, but not the actual values of the enhancement. Furthermore, high-field experiments are not suitable for this purpose, because the pulse sequences have been optimized for a complex with two  $^{15}\text{N}$  nuclei, whereas at lower  $^{15}\text{N}$  abundance a fraction of the complexes have only one  $^{15}\text{N}$  nucleus (at low  $^{15}\text{N}$  abundance the fraction of the complexes with two  $^{15}\text{N}$  nuclei become negligible). The parameters of the complexes with one or two  $^{15}\text{N}$  nuclei are quite different; consequently, for such complexes optimal  $\epsilon$  may be achieved for different  $\omega_1$  and  $\Delta$  values. As a result, direct comparison of  $\epsilon$  values measured at different  $^{15}\text{N}$  abundance becomes problematic.

To get around this problem, we have decided to measure  $\epsilon$  at ultralow magnetic fields, where the  $^1\text{H}$  and  $^{15}\text{N}$  nuclei become strongly coupled and “spontaneous” polarization transfer without rf-excitation between them becomes efficient. This is the essence of the SABRE-SHEATH method.<sup>21,37,38</sup> It is important to note that at ultralow fields the chemical shift difference of the protons bound to the SABRE complex is of no importance, so that symmetry breaking (and hence, singlet-triplet conversion) occurs solely due to magnetic non-equivalence. Furthermore, there is no need to analyse the spin dynamics in additional complexes, which strongly affect the *para*-to-*ortho* conversion at high field. Although at ultralow fields we are unable to run experiments to elucidate the relative populations of different spin states since we cannot apply any pulses to the protons, we can measure  $\epsilon$  over a wide range of fields.

Comparison of the SABRE field dependences measured as a function of the  $^{15}\text{N}$  enrichment (at the same total concentration of  $^{15}\text{N}$ -Py and  $^{14}\text{N}$ -Py) is shown in Fig. 8. The measured signal enhancement indicates that the SABRE polarization efficiency at ultra-low field increases when the abundance of  $^{15}\text{N}$  nuclei is lowered. It is noteworthy that the position of the maximum of the field dependence also depends on the concentration of labelled substrate, which is due to the difference in the parameters of the spin system of the SABRE complex for each specific solution.

We attribute these results to conversion between different forms of  $\text{H}_2$ , driven by the interaction with  $^{15}\text{N}$  spins. Such interactions not only give rise to spin order transfer to the nitrogen spins, but also to singlet-to-triplet conversion in bound  $\text{H}_2$ , by perturbing the spin state of  $\text{H}_2$ . As a consequence, at high concentration of  $^{15}\text{N}$  isotopes,  $p\text{H}_2$  is converted to thermally polarized  $\text{H}_2$ , which can no longer provides any NMR enhancements. When the abundance of  $^{15}\text{N}$  nuclei is



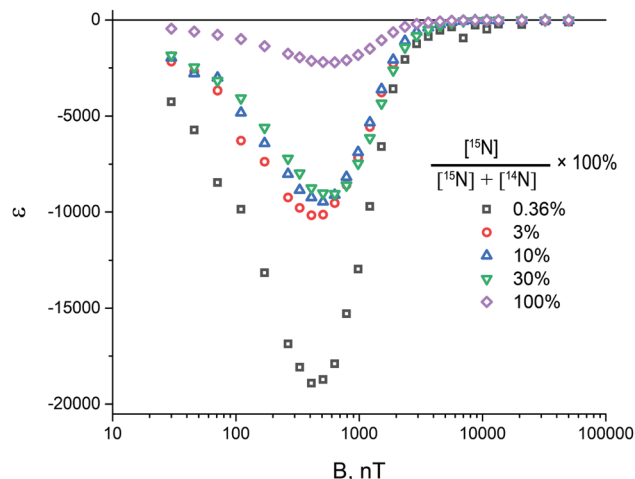


Fig. 8 Magnetic field dependence of the  $^{15}\text{N}$  signal enhancement under ZULF conditions ( $5\text{ nT} < B_0 < 100\text{ }\mu\text{T}$ ), obtained for the percentage of  $^{15}\text{N}$  pyridine in the solution, measured for  $[C] = 2\text{ mM}$ , while  $[S] = 40\text{ mM}$  (= total concentration of  $^{14}\text{N}$ -Py and  $^{15}\text{N}$ -Py) was kept constant. We used solutions without removing  $\text{Cl}^-$ .

low, the source spin order survives for a longer period of time, giving rise to a stronger  $^{15}\text{N}$  signal enhancement. Our observations also explain why  $^{15}\text{N}$ -NMR enhancement factors are so high, of the order of 30 000 for natural isotopic abundance (which is only 0.365%).<sup>22</sup> The absolute signal intensity, which is given by the product of the concentration (proportional to  $\eta_{\text{N}}$ , the fraction of  $^{15}\text{N}$  containing molecules) and the maximal enhancement  $\epsilon_{\text{opt}}$ , is the highest for large  $\eta_{15\text{N}}$ . The reason is that at low  $\eta_{15\text{N}}$   $^{15}\text{N}$  containing molecules very seldom bind to the SABRE complex, resulting in slow polarization build-up and lower signal intensity.

Another effect, which supports our conclusions, is the striking dependence of SABRE enhancement levels on the  $p\text{H}_2$  bubbling pressure. The results of SABRE experiments performed at bubbling pressures in a range from 5 to 25 bars are presented in ESI† (Fig. S3). The linear growth of SABRE enhancement with increasing bubbling pressure (which leads to an increasing  $p\text{H}_2$  concentration in the sample) demonstrates that the excess of fresh  $p\text{H}_2$  in the solution attenuates the negative effect of singlet–triplet conversion. However, it is noteworthy, that even at 25 bar with reasonable gas flow rates, the enhancement level does not reach saturation, which possibly indicates the substantial effect of singlet–triplet conversion even at ultra-low field conditions.

## Conclusions

Our work gives a clear evidence that singlet–triplet conversion in bound  $\text{H}_2$  plays an important role in SABRE experiments. Due to the spin dynamics, this conversion becomes fast in the Iridium complex. An important feature of this conversion is that it favours one of the three triplet states, here to the central triplet state, producing polarized  $\sigma\text{H}_2$  that does not obey a Boltzmann distribution. This can be unequivocally proven by

running polarization transfer experiments with an additional pulse applied to the proton channel. Such experiments allow one to estimate the populations of the three spin states of  $\sigma\text{H}_2$  experimentally. In the present case, the additional proton pulse giving rise to a strong additional gain in  $^{15}\text{N}$  signal, which is more than 10-fold in some cases. Hence, studying the conversion process is not a matter of pure curiosity, but it is of great practical importance for the performance of the SABRE method. In addition, we demonstrated that the conversion process is strongly affected by the presence of  $^{15}\text{N}$  nuclei, which make the  $p\text{H}_2$ -nascent protons in the complex magnetically inequivalent. This effect is of great importance for polarization transfer experiments at ultralow fields, where the signal enhancement decreases when the isotopic abundance of  $^{15}\text{N}$  nuclei is increased. The reason is that the limited source of  $p\text{H}_2$ -derived polarization is exhausted upon polarization transfer to  $^{15}\text{N}$  nuclei.

Thus, we can conclude that spin order conversion processes from  $p\text{H}_2$  to  $\sigma\text{H}_2$ , and within the triplet manifold of  $\sigma\text{H}_2$  are an important for the success of PHIP and SABRE experiments. We believe that consideration of these processes and corresponding optimization of experimental parameters (concentrations, extent of isotopic labelling,  $p\text{H}_2$  pressure, parameters of NMR pulse sequences) can significantly improve the signal enhancements that can be achieved by PHIP and SABRE.

## Conflicts of interest

There are no conflicts to declare.

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