Spin density localization and accessibility of organic radicals affect liquid-state DNP efficiency†

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We report a large variation in liquid DNP performance of up to a factor of about five in coupling factor among organic radicals commonly used as polarizing agents. A comparative study of 1H and 13C DNP in model systems shows the impact of the spin density distribution and accessibility of the radical site by the target molecule.

In the past two decades, dynamic nuclear polarization (DNP) has become one of the most important tools to tackle the long-standing sensitivity issue in modern nuclear magnetic resonance (NMR). 1,2 In a DNP experiment, polarization is transferred from higher polarized electron spins by resonant microwave (mw) irradiation to the target nuclei. Electron spins are often added to the investigated sample in the form of exogenous polarizing agents (PAs), usually organic radicals.

DNP has been successful in the solid-state, where it is routinely applied to various systems in biology and material science, and enables an extraordinary saving of experimental time. 3,4 Part of these achievements were possible thanks to the optimization of bi-radicals as excellent PAs for the polarization transfer via cross-effect. 5–7

The polarization transfer in liquids is dominated by the Overhauser effect (OE), 8 strongly depends on the chosen target molecule/PA system as well as on the external magnetic field strength. 9,10 Increasing the efficiency of OE-DNP is of particular importance. At high magnetic fields, the choice of an optimal PA would help the application of the method in analytics and high resolution NMR spectroscopy. 11–15 Furthermore, higher NMR enhancements could boost the applications of OE-DNP at low fields (≤ 2 T), which include in-flow hyperpolarization for magnetic resonance imaging 16,17 or chromatography. 18,19

NMR relaxometry of low-γ nuclei 20 hydration dynamic studies, 21,22 and DNP-NMR spectroscopy. 23–25

In the experimental practice, nitroxide derivatives (NODs) have been established as optimal PAs for OE-DNP in the liquid state at room temperature and ambient pressure. 26,27 In water, they perform better than trityl radicals at various fields (from 0.34 T to 3.4 T), 28,29 and they are the benchmark for 1H-DNP at low fields (enhancements ε = ~178 ± 13 for water doped with TEMPONE). 30,31 An improvement of nitroxide derivatives performance was realized by linking a C60 (fullerene) moiety to a TEMPO based radical, which increased the saturation factor of the electron spin transition. 32 Also BDPA has been employed in numerous DNP studies in solid and in liquids, the latter particularly at high fields (≥ 5 T). 33,34 However, despite its favourable saturation behaviour, the performance of BDPA in liquids as compared to NODs appeared moderate, but a systematic study has been missing.

Despite the available data, it is difficult to compare the PA’s performance independently of the experimental conditions, such as mw power and resonant cavity, magnetic field, radical concentration, and target nuclei. Although several mechanistic studies on 1H 27,35,36 and 13C 37,38 have been reported, the detailed role of the PA remains unclear. Very recently, we investigated the case of fullerene nitroxides in comparison to TEMPONE, 34,39 and found that small structural reorientations can impact the DNP efficiency at both low and high magnetic fields. 39 Therefore, we proposed that the chemical structure of the PA molecule must play an essential role within the OE-DNP mechanism.

To examine this hypothesis, in this work we systematically investigate and compare the performance of several PAs in OE-DNP in the liquid state and show that NODs, with subtle differences in their chemical structure, behave differently from each other. To ensure comparability of the results, we utilized model solvents in which the polarization transfer mechanisms are known. DNP was performed at low fields (0.34 T and 1.2 T), where an independent determination of all OE parameters was feasible with our available instrumentation. The trend that we
observe in DNP performance is interpreted in terms of radical mobility, solvent accessibility, and spin density distributions, with the support of DFT calculations. Our investigation allows to recognize specific characteristics of the PA structure which are a prerequisite for effective OE-DNP in liquids.

Overhauser DNP is based on a cross-relaxation process between an electron spin system and a nuclear spin system mediated by molecular motions.\textsuperscript{8,35,40} The hyperfine coupling driving the relaxation consists of two contributions: (i) dipolar coupling, mediated by diffusion;\textsuperscript{35,41} (ii) scalar coupling, due to Fermi contact interactions, usually mediated by molecular collisions.\textsuperscript{11,42} The complex interplay of these two mechanisms is reflected in a single parameter, the coupling factor $\zeta$, which varies between $\zeta = 0.5$ (pure dipolar) and $\zeta = -1$ (pure scalar). $\zeta$ is defined by the Overhauser equation:\textsuperscript{8}

$$e = \frac{(L)}{I_0} = 1 - \xi s f_{\text{sat}}/\gamma_n$$  

(1)

where $e$ is the NMR signal enhancement, which is defined as the ratio between the expectation value of the nuclear magnetization under mw irradiation $(L)$ and the one at thermal equilibrium $I_0$. $\gamma_e$ and $\gamma_n$ are the gyromagnetic ratios of the electron spin ($\gamma$) and the nuclear spin ($n$), respectively. The saturation factor $s$ ($0 \leq s \leq 1$) is a measure of how far the electron spin is driven out of equilibrium by the applied mw irradiation.\textsuperscript{31} The leakage factor $f$ ($0 \leq f \leq 1$) accounts for the paramagnetic relaxation contribution to the nuclear relaxation term, and depends on the PA concentration. Since $s$ and $f$ can be tuned by the mw power and the radical concentration, respectively, the coupling factor $\zeta$ defines the net efficiency of a specific PA in a given system, and can be calculated with eqn (1) once $s$, $f$, and $e$ are independently determined.

In this study, we compare the DNP efficiency, represented by $\zeta$, of six organic radicals that differ in their chemical structure (Fig. 1). Within the NODs, TL and TN have both a six-membered ring but a different backbone. DTBN lacks the piperidine backbone and is therefore very mobile, a feature that, in principle, makes this radical ideal for DNP modulated by fast diffusion processes. In contrast, TN-py has the same backbone structure of TN but has two hydropyrane rings in the direct vicinity of the NO group.\textsuperscript{51} We also consider the fullerene-nitroxide FN-2a, which has already been reported as a PA in the context of $^1$H and $^13$C DNP.\textsuperscript{24,32,39} Finally, we compared NODs with BDPA. The organic radicals were dissolved in toluene (C$_7$H$_8$), chloroform (CHCl$_3$) and tetrachloromethane (CCl$_4$), with concentrations in the range 0.5–16 mM (see ESI for details).

\textbf{Table 1.} Overhauser parameter $f$, $s$, $\varepsilon$ and $\zeta$ for $^{13}$C at 1.2 T and $^1$H DNP at 0.34 T for different PAs in chloroform. Uncertainties for $f$ and $\zeta$ are 10% while errors for $e$ and $\zeta$ are up to 15% and 25%, respectively (ESI). Radical concentrations are in the range 0.5–16 mM (see ESI for details).

| Radical | $f$ ($^{13}$C) | $s$ ($^{13}$C) | $\varepsilon$ ($^{13}$C) | $\zeta$ ($^{13}$C) | $f$ ($^1$H) | $s$ ($^1$H) | $\varepsilon$ ($^1$H) | $\zeta$ ($^1$H) |
|---------|-------------|-------------|----------------|-------------|-------------|-------------|----------------|-------------|
| DTBN    | 0.88        | 0.04        | 31             | -0.33       | 0.99        | 0.76        | -181           | 0.37        |
| $^{15}$N-TN | 0.85        | 0.18        | 200            | -0.49$^{24}$ | 0.99        | 0.92        | -224           | 0.37        |
| TL      | 0.92        | 0.07        | 59             | -0.35       | 0.97        | 0.45        | -85            | 0.30$^{39}$ |
| TN-py   | 0.89        | 0.10        | 55             | -0.23       | 0.99        | 0.78        | -156           | 0.31        |
| FN-2a   | 0.89        | 0.30        | 370            | -0.53$^{24}$ | 0.99        | 0.87        | -116           | 0.20$^{39}$ |
| BDPA    | 0.40        | 1.00        | 122            | -0.12       | 0.99        | 1.00        | -11            | 0.018       |

$^a$ Uncertainty of this measurement is $\sim$ 15%.

Fig. 2a and b display $\zeta$ for $^{13}$C and $^1$H, respectively, in different solvent/PA systems. $^{13}$C-DNP coupling factors $\zeta$ (Fig. 2a) are negative, a fact which indicates a scalar-dominated polarization transfer,\textsuperscript{8,40} and show an interesting, quite unexpected behaviour. Indeed, in CCl$_4$, $\zeta$ is strongly dependent on the PA, and goes from $-1$ to $0.1$. This indicates a factor of $\sim$ 5 variation in DNP efficiency. Besides these large differences, also variations among structurally similar small NODs (TL, DTBN and TN) are observed. In CHCl$_3$, the total variation of $\zeta$ (from BDPA to FN-2a) is a factor of $\sim$ 4 (Table 1), whereas it is a factor of 1.5 among the small NODs ($\zeta$(DTBN) = 0.33 and $\zeta$(FN-2a) = 0.49, Table 1).

$^1$H-DNP coupling factors show a different trend. Firstly, $\zeta$ is positive, consistent with a mechanism dominated by dipolar relaxation. Specifically, $\zeta$ varies from $\zeta = 0.24 \pm 0.04$ for TN-py up to a maximum $\zeta = 0.42 \pm 0.1$ for DTBN in toluene, which is close to the theoretical limit of $\zeta = 0.5$.\textsuperscript{8,40} Among the NODs, $\zeta$
where the coupling factor in 13C-DNP arises from an interplay of 1H-DNP (such as 1H-DNP) does not necessarily correlate with an efficient coupling factors shown in Fig. 2a. Indeed, we reported in previous studies,24,42 and it is predicted by the theory, 8 that poor performance of dipolar dominated DNP (such as BDPA) is larger, ranging from a SAS3.2 Å = 29.5 Å 2 for DTBN to SAS1.2 Å = 35.1 Å 2 for TN (Fig. 3b and d). These large SAS areas are mainly due to the accessibility of the O atom, while the N atom remains buried. For TN-py, a conformational analysis shows four energetically accessible conformers at room temperature, which differ in the orientation of their hydropyrane rings, i.e. open and half-open (ESI).49 While SAS1.2 Å ~ 32 Å 2 for the open conformation, the accessibility of the radical site is hampered in the half-open ones (SAS1.2 Å ~ 11 Å 2) (Fig. 3c).

Overall, the trend of the SAS depicted in Fig. 3d correlates with our observations of ζ(13C) (Fig. 2a) with the exception of the very large ζ of FN-2a. This can be interpreted phenomenologically with the Pulse model for molecular collisions (eqn (2)), which describes |ζ| ∝ τPulse. Intuition suggests that the accessibility of the radical site should mainly impact the collision rate τPulse. To support this, we note that the field dependent term Jcont (τcont,ω) in eqn (2) is determined by the duration of each encounter. In previous studies,24,42 we showed that, in CCl4 and CHCl3 doped with TN, the main contribution comes from τcont ≈ 0.5–2 ps. The same could be reasonably assumed for other NODs (DTBN, TL) in the same solvent and at the same temperature. Nonetheless, structural reorientations on the PA molecule can introduce additional contributions to Jcont(τcont,ω,)}
This is particularly relevant for the specific case of FN-2a, whose outstanding performance is likely caused by a particularly favourable collision time scale ($\tau_{\text{cont}} \sim 4–12$ ps) which maximizes $J_{\text{cont}}(\varphi_{T}, \varphi_{\text{cont}})$ at this magnetic field (1.2 T). In our previous report, this was attributed to the transition of the six-membered ring from a chair to an unstable half-chair conformation, enabled by the asymmetry of the backbone linker. Similar dynamics are not expected in TL, TN, and DTBN but cannot be excluded for TN-py.

In a second step, we considered the static complex PA/target molecule and used DFT calculations to compute the hyperfine coupling constant $A_{\text{FC}}$ to the target nucleus.38,42 $A_{\text{FC}}$ of the C nucleus in CHCl$_3$ was calculated for at least four optimized geometries $i$ for each complex PA/CHCl$_3$ (ESI†). Due to the tendency of the H atom of CHCl$_3$ to form hydrogen bonds, we distinguish an energetically favoured complex where the H is pointing towards the radical (“via H”), and a less favoured one, where the Cl atom is the closest to the radical (“via Cl”). The hyperfine coupling $\langle A_{\text{FC}} \rangle$ was calculated as the weighted average of $A_{\text{FC}}$ over the relative free energy $E_{\text{rel}}$, of each configuration $i$, i.e. $\langle A_{\text{FC}} \rangle = \sum_i A_{\text{FC}} \cdot P_i / \sum_i P_i$ where $P_i = e^{-E_{\text{rel}}/k_{\text{B}}T}$, with $T = 300$ K. $\langle A_{\text{FC}} \rangle$ calculated for DTBN, TL, and TN are similar and between 11.8 MHz and 14.6 MHz. The lack of the piperidine backbone structure in DTBN seems to slightly affect the hyperfine coupling to the C nucleus. Notably, the $\langle A_{\text{FC}} \rangle$ of TN-py calculated for both the open and the half-open conformations are smaller than the other NODs (Fig. 4), which agrees with our experimental observation of a lower $\zeta$ (13C). This is justified within the Pulse model, where the spectral density $J_{\text{Pulse}}$ scales with $\langle A_{\text{FC}} \rangle$ (eqn (2)).

Finally, the $\langle A_{\text{FC}} \rangle$ calculated for the complex BDPA/CHCl$_3$ is 0.26 MHz, significantly lower than $\langle A_{\text{FC}} \rangle$ calculated for NODs (Fig. 4 and ESI†). This reveals the weak ability of BDPA to transfer spin density on the C nucleus, despite more than 50% of the spin density is readily accessible on the phenylene rings. Therefore, the lack of an accessible site where a large spin density is localized seems to be detrimental for scalar-driven DNP.

In conclusion, our study revealed that differences in chemical structure of organic PAs commonly used in DNP can influence the performance of OE-DNP, up to a factor of 5 when the mechanism is scalar-dominated. We identified features that should be considered for designing an optimal PA. Specifically, a localized spin density is preferred over a distributed one, because it increases the hyperfine coupling with the target nuclei. Secondly, the accessibility of the radical site, which affects the collision rate with the target molecule, should not be compromised by structural design (BDPA) or
confomational rearrangements (TN-py). We note that these characteristics, which can be inferred a priori from the structure of the PA, affect the field independent term of the scalar relaxation and should therefore be taken into account also for OE-DNP at high magnetic fields.

Conflicts of interest
There are no conflicts to declare.

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