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High Field Dynamic Nuclear Polarization NMR with Surfactant Sheltered Biradicals

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ABSTRACT: We illustrate the ability to place a water-insoluble biradical, b'Tbk, into a glycerol/water matrix with the assistance of a surfactant, sodium octyl sulfate (SOS). This surfactant approach enables a previously water insoluble biradical, b'Tbk, with favorable electron–electron dipolar coupling to be used for dynamic nuclear polarization (DNP) nuclear magnetic resonance (NMR) experiments in frozen, glassy, aqueous media. Nuclear Overhauser enhancement (NOE) and paramagnetic relaxation enhancement (PRE) experiments are conducted to determine the distribution of urea and several biradicals within the SOS macromolecular assembly. We also demonstrate that SOS assemblies are an effective approach by which mixed biradicals are created through an assembly process.

INTRODUCTION

Nuclear magnetic resonance is the dominant spectroscopic tool for the characterization of most chemical systems. In particular, solid-state NMR (ssNMR) has shown promise in characterizing disordered biological complexes (e.g., membrane proteins and amyloid fibrils) which are inaccessible via traditional diffraction-based methods. However, the success of these experiments is often limited due to the low Boltzmann polarization of nuclear spins, leading to extended acquisition times (i.e., >weeks). High field dynamic nuclear polarization (DNP) is an approach that dramatically increases the sensitivity of NMR experiments. Specifically, DNP can hyperpolarize NMR-active nuclei, yielding a gain in sensitivity of 2–3 orders of magnitude. High-field DNP involves transferring electron polarization to nuclei via one of several possible mechanisms upon microwave irradiation of the electron EPR transitions. Although DNP was conceptually conceived and demonstrated in the 1950s, a renaissance in the methodology has occurred in the past few years. This is due largely to the development of high-power microwave sources (i.e., gyrotrons) and improvements in instrumentation (i.e., cryogenics and MAS probe technology) required to conduct these experiments at high fields (>5 T), and this has served as a major driving force for the commercialization of DNP instrumentation. A second and equally critical component of this methodology is access to stable radicals from which the polarization is ultimately derived. The DNP mechanism judged to be most efficient in high-field DNP NMR experiments is the cross effect (CE) mechanism, whereby hyperpolarization occurs through a three-spin “flip–flop–flip” process involving two electrons and a nucleus. The dominant mechanism in a given experiment is determined in part by the relative magnitudes of the electron homogeneous (δ) and inhomogeneous (Δ) line widths and the nuclear Larmor frequency (ωN). The CE is dominant when the polarizing agents satisfy, Δ > ωN > δ, as is the case for nitroxide containing radicals. Fine-tuning the resonance frequencies of the two electrons to match the nuclear Larmor frequency optimizes the signal enhancement, ε, that is achievable, εmax ≈ 660 (γe/γH) for 1H. The electron–electron coupling and frequency separation can be altered in practice by synthetically modulating the relative orientation and interelectron distance, an approach that has been the mainstay of biradical design for the past decade. For example, the molecule b'Tbk (Scheme 1) ostensibly has a superior geometry and electron–electron dipolar coupling as compared to TOTAPOL but lacks solubility in biological friendly solvents. SPIROPOL has superior solubility to b'Tbk but has decreased dipolar electron coupling. Very recently, Tordo and co-workers introduced two new radicals based on BTurea, and Pypol and AMUpol display very promising gains in sensitivity for 1H DNP NMR, at temperatures between 100 and 160 K.

Interest in applying DNP to the investigations of biological materials, where NMR signal intensity is of extreme importance, has solidified glycerol/water as a dominant medium for DNP experiments. Glycerol/water mixtures have the dual benefit of being suitable for biological samples and forming a solid glass regardless of cooling rate. Glass formation is particularly important to ensure a homogeneous distribution of the polarizing agent, the inhibition of ice formation to prevent protein denaturation at cryogenic...
temperatures (i.e., <110 K), and the promotion of effective spin-diffusion to rapidly transfer polarization throughout the sample.\textsuperscript{19,23} Accordingly, the pursuit of biradicals has primarily been limited to those that are soluble in glycerol/water mixtures. This limitation can be particularly frustrating when ostensibly superior polarization agents can be conceived and synthesized but are insoluble in glycerol/water.\textsuperscript{18,20,25,26} For example, after the report of bTbk,\textsuperscript{27} a polarization agent with a ε superior to TOTAPOL in DMSO/water, several years lapsed in an effort to reproduce the enhancements in aqueous solvent, efforts that were only partially successful in the advent of SPIROPOL.\textsuperscript{17}

The use of surfactants is a common, cost-effective method to dissolve organic compounds in aqueous environments,\textsuperscript{28–30} yet this approach has not been employed for the dissolution of polarization agents in water. In this communication, we illustrate the ability to place water-insoluble bTbk into a glycerol/water matrix with the assistance of a surfactant. This surfactant approach adds bTbk as well as other water-insoluble radicals to the armamentarium of biradicals available for aqueous DNP. Further, we explore a common solvent system in order to benchmark all (bi)radicals, even water-insoluble radicals, against each other.

\textbf{EXPERIMENTAL SECTION}

Isotopically enriched urea\textsuperscript{13}C (99% 13C) and D\textsubscript{2}O (99%) were purchased from Cambridge Isotope Laboratories (Andover, MA, USA). Sodium octyl sulfate-d\textsubscript{17} and D\textsubscript{2}O were purchased from Cambridge Isotope Laboratories (Andover, MA, USA). Sodium octyl sulfate-d\textsubscript{17} was purchased from Cambridge Isotope Laboratories (Andover, MA, USA), and glycerol-d\textsubscript{8} (98% 2H) was purchased from DyNuPol, Inc. (Newton, MA, USA). The surfactant SPIROPOL and bTbk were prepared according to published procedures,\textsuperscript{17,18} while TOTAPOL\textsuperscript{19} was purchased from DyNuPol. The monoradical Finland trityl was purchased from Sigma-Aldrich. All chemicals were used as received.

**Sample Preparation.** Samples were prepared in air by weighing solids directly into a glass vial. Solvent was added to solids which were dissolved with gentle heating and agitation, if necessary. Samples were never subjected to sonication, as it leads to rapid degradation of the nitroxide moiety.\textsuperscript{31} Samples were then transferred to either NMR tubes (solution studies) or sapphire rotors (solid state DNP studies) as applicable.

**Nuclear Overhauser Effect (NOE) Experiments.** NOE experiments were performed on a Varian 400 MHz spectrometer using the NOE difference macro in VNMR with the following parameters: acquisition time = 3.0 s; preacquisition delay = 10 s; pulse width = 9.0 ms; pulse power = 60 dB; steady state scans = 2; decoupling nucleus = 1H; saturation delay = 5 s; number of transients = 64; saturation power = 15 dB (HOD), 5 dB (urea); reference saturation frequency = 5000 Hz.

**Paramagnetic Relaxation Enhancement (PRE) Experiments.** Four NMR samples were made containing urea-$^{13}$C (1 M) and SOS (0.75 M SOS-H) in glycerol-d\textsubscript{8}/D\textsubscript{2}O/H\textsubscript{2}O (0.3 mL; 60/30/10) with either no radical or 10 mM bTbk, TOTAPOL, or SPIROPOL. Into each of these NMR samples, a sealed glass capillary tube containing 10% C\textsubscript{6}H\textsubscript{6} in C\textsubscript{6}D\textsubscript{6} was inserted; the C\textsubscript{6}H\textsubscript{6}/1H NMR resonance is free of PRE under all conditions and serves as an internal standard. A well-shimmed 1H NMR experiment was acquired for each sample. The line width of a resonance (Δ\textsubscript{pp}ω) is proportional to the nuclear transverse relaxation rate. The presence of a paramagnet shortens T\textsubscript{2} and enhances the relaxation rate, R\textsubscript{β}, where the line width provides a direct readout of R\textsubscript{β}*. The observed relaxation rate, R\textsubscript{β} = Δω\textsubscript{pp}ω = 1/T\textsubscript{2}*. The intrinsic line width of each resonance was taken to be those of the paramagnet-free sample (Δω\textsubscript{pp}ω = R\textsubscript{β}ω), and the observed line width in the paramagnetic samples, Δω\textsubscript{pp}ω = R\textsubscript{β}ω = 1/T\textsubscript{2}*, is the difference from the intrinsic line width caused by the PRE (i.e., the spin–paramagnet interactions),\textsuperscript{32–34} PRE = R\textsubscript{β}ω = R\textsubscript{β}ω − R\textsubscript{β}ω.

**Solubility Measurements.** The solubility of the three biradicals was determined by serial addition of material or dilution with the appropriate solvent system. For example, bTbk (10.0 mg; 10 mM) was added to 2.5 mL of glycerol-d\textsubscript{8}/D\textsubscript{2}O/H\textsubscript{2}O (60/30/10) and stirred with gentle heating (50 °C). After 30 min, precipitate persisted, and the concentration of bTbk was reduced by half by the addition of solvent. The solution was stirred and heated for 30 min, and this heating/stirring/dilution process was repeated until the failure of the 1 mM solubility experiment. For SPIROPOL and TOTAPOL, the serial additions of material were concluded (in 10 mM increments, followed by 1 mM increments) if precipitate remained after 30 min of heating and stirring.

**Dynamic Nuclear Polarization NMR Measurements.** Dynamic nuclear polarization magic-angle spinning NMR experiments were performed on a home-built spectrometer, consisting of a 212 MHz (1H, 5 T) NMR magnet (courtesy of Dr. David Ruben, FBML, MIT) and a 139.65 GHz cyclotron resonance maser (i.e., gyrotron) generating high-power microwaves up to 14 W. MAS NMR spectra were recorded on a home-built cryogenic 4 mm quadrupole resonance (1H, 13C, 15N, and ε) DNP NMR probe equipped with a Kel-F stator (Revolution NMR, Fort Collins, CO). Microwaves are guided to the sample via a circular overmoded waveguide whose inner surface has been corrugated to reduce mode conversion and ohmic losses. Sample temperatures were maintained at 83 (±1) K, with a spinning frequency, ω\textsubscript{m}/2π = 4.0 kHz. 13C(1H) cross-polarization\textsuperscript{35} experiments using a 1.5 ms contact time were acquired under continuous microwave irradiation. Sample temperatures were measured using a Neoptix (Quebec, Canada) thermocouple which were calibrated between 3 and 353 K. High-power TPPM\textsuperscript{36} proton decoupling (1H γB/2π =...
100 kHz) was used during acquisition. Buildup times ($T_B$) were determined using a saturation recovery experiment. The recycle delay was chosen as $T_B \times 1.3$, yielding optimum sensitivity per unit of time. Microwave power was kept constant at 8 W using a PID control interfaced within Labview. $^1$H cross-effect conditions were optimized for each radical by sweeping the main NMR field using a $\pm 750$ G sweep coil in order to sit at the maximum positive enhancement position within the DNP field profiles. $^{17,19,27}$ Samples were contained in 4 mm sapphire rotors equipped with a Vespel drive tip and Kel-F spacer.

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**RESULTS AND DISCUSSION**

$b$Tbk is only soluble in glycerol/water solution upon the addition of surfactant. Addition of sodium octyl sulfate (SOS; 0.57 M) to a glycerol-$d_6$/D$_2$O/H$_2$O ($v/v/v$ 60/30/10) $^{57}$ solution of urea (1 M) containing precipitated bTbk (10 mM) followed by agitation, and gentle heating produces a stable yellow-orange homogeneous solution. The addition of the SOS does not visually disrupt the glass formation of the solvent system. Solubility testing reveals bTbk is not soluble with SOS concentrations below 0.57 M.

The intermolecular nuclear Overhauser effect (NOE) is a powerful tool for characterizing a complex solution. In an NMR tube containing 1 M urea and SOS (0.75 M) in glycerol-$d_6$/D$_2$O/H$_2$O ($v/v/v$ 60/30/10), an NOE experiment irradiating the water/glycerol peak at maximum power provides an indication of solvent exposure of the species in solution. Intermolecular NOEs are difficult to quantify between species especially in an incomplete saturation situation, but the NOE from the solvent to the urea is approximately $10 \times$ the enhancement observed in the same solution from the solvent to SOS. Further, the NOEs extend across the entire SOS alkyl chain, with each internal methylene and the methyl resonance experiencing an NOE approximately $0.25 \times$ the methylene $\alpha$ to the sulfate moiety. In a separate experiment where the urea peak is saturated, the NOE appears only on the water/glycerol resonances with no detectable NOE from the urea to the SOS. Taken together, these observations suggest that urea resides mainly in the bulk solvent, but the water/glycerol solvation extends to the core of the SOS macromolecular structure.

The short- to medium-range distance (<6 Å) $^{34}$ information available from NOE experiments can be complemented with paramagnetic relaxation enhancement (PRE) measurements whose effects extend upward of 25 Å. $^{38}$ Indeed, simple $^1$H NMR spectra of bTbk/SOS solutions compared to a paramagnet-free SOS-containing solution indicate the preferred
location of the biradical in solution. The NMR line widths are proportional to the nuclear spin–spin relaxation time constant, $T_2$ via the Solomon equation,$^{3,13}$ and altering the nuclear $T_2$ by paramagnetic relaxation changes the line width, thereby providing a direct readout of the proximity of the biradical. A sealed glass capillary of benzene in benzene-$d_6$ provides an internal standard that is free from PRE under all conditions. Our PRE experiments suggest that bTbk preferentially occupies the interior of the SOS assembly and is uniformly relaxing the SOS methylene moieties. Despite being localized in the interior of the SOS macromolecular structure, bTbk exhibits PRE to the urea-$13\text{C}$ resonance; however, the glycerol enhancements were within experimental error of the urea-$13\text{C}$ signal. This indicates that efficient electron–$1\text{H}$ communication and $1\text{H}$–$1\text{H}$ spin-diffusion effectively transfer a global $1\text{H}$ enhancement across the whole system.

The PRE experiment was repeated using TOTAPOL and SPIROPOL, and these results are shown in Figure 3. The trend of biradical PRE to the solvent –OH resonance is proportional to the solubility of the biradicals in glycerol/water mixtures without SOS: TOTAPOL is highly soluble (∼50 mM), SPIROPOL is moderately soluble (∼10 mM), and bTbk is insoluble (∼1 mM). Accordingly, the magnitude of the PRE on the SOS resonances runs inversely with biradical solubility as does the PRE$_{\text{urea}}$ due to each biradical. This observation is significant, as does the PRE$_{\text{urea}}$ due to each biradical. This observation suggests that the urea may be the most soluble in the reaction media (i.e., those that do not need SOS to become soluble) will have the least contact with the urea and exhibit the smallest enhancement. This observation could be used to inform the DNP NMR studies upon complicated samples. For example, the choice of biradical would be prudent when one wishes to study cell membranes versus intra/extra-cellular environment.

The synthetic generation of heterobiradicals (cf. BDPA-TEMPO biradicals) has been the thrust of our research effort. Although this area of research has tremendous potential, we posited that the hydrophobic environment at the interior of the SOS macromolecular structure might allow for the self-assembly of such biradicals. Toward this end, we examined the solubility of several monoradicals in 0.75 M SOS: BDPA, alkyl-derivated BDPAs, and trityl radical were all insoluble. Finland trityl, a more hydrophilic version of the parent trityl radical, was adequately soluble. DNP of urea in 0.57 M SOS (5% H) with 10 mM Finland trityl and 10 mM TEMPO in the usual solvent mixture gave $\varepsilon = 70\%$; see the Supporting Information (all enhancements reported for the SOS system were $\pm 1\%$ error).
are collected in Table 1). This is approximately the same \( \varepsilon \) measured for 10 mM TEMPO and 10 mM Finland trityl in free solution.\(^{10} \) The remarkable difference is in the buildup times for the mixed biradical: 5 s with SOS vs 10.5 s without SOS. This shorter buildup time allows for an experimental recycling delay to be reduced by a factor of 2 compared to the system without SOS. The average electron–electron dipolar coupling for the three biradicals \( \text{vide supra} \) is between 25 and 30 MHz, whereas a 20 mM (10 mM/10 mM) mixed monoradical is \( \sim \)0.6 MHz. Initial studies using the mixed monoradical approach for direct DNP of \( ^{1}H \) (\( T_{2} \approx 5 \) s)\(^{14} \) and \( ^{13}C \) in free solution utilized a 40 mM electron concentration (twice the molar concentration) for effective DNP enhancements with a dipolar coupling being \( \sim \)1.2 MHz.\(^{40} \) The reduced buildup time constant observed is consistent with a stronger electron–electron dipolar coupling caused by the proximity of the monoradicals trapped within the surfactant. A thorough screening of self-assembled mixed biradicals and the origin of the attenuated buildup time will be explored in the future.

## CONCLUSION

The addition of a surfactant, sodium octyl sulfate, to glycerol/water solutions allows for the acquisition of DNP data for classically water-insoluble radicals. This approach allows for the first time the comparative testing of three biradical polarization agents in a side-by-side manner. The stark attenuation of the DNP enhancement of TOTAPOL in SOS-containing glycerol/water suggests that this bi-nitroxide may not be the best biradical for surfactant-like situations, including cell membranes. Further, judicious choice of the biradical could allow, for example, selective enhancement of membrane proteins without paramagnetic relaxation. The possibility of rapidly screening mixed biradicals, like the Finland trityl/TEMPO system, is an exciting advance for polarization agent synthesis and may guide future synthetic efforts. Indeed, the outlook for surfactant encapsulated radical DNP on various chemical systems seems promising, with the recent paper by Mao et al. using a similar approach with cyclodextrin.\(^{41} \) Combined with the wide array of mono- and biradicals available,\(^{17,18,20,21,40,42} \) this approach should offer effective methods to polarize important chemical systems opening up new scientific avenues.

## ASSOCIATED CONTENT

### Supporting Information

Tables showing CP-MAS DNP enhancements, buildup times, and inter-radical distances of the biradicals used in this study and CP-MAS DNP enhancements and buildup times for the various concentrations of \( b'TbK \) studied. Figures showing CP-MAS DNP, \( ^{1}H\text{-NMR} \), and \( ^{1}H\text{ NOE difference NMR spectra.} \)

This material is available free of charge via the Internet at [http://pubs.acs.org](http://pubs.acs.org).

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