[5] To prevent contamination by the amine, **1a** should be purified by column chromatography on neutral silica gel.
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[7] ^{31}P NMR (109 MHz, [D$_6$]DMSO, H$_3$PO$_4$): the initial species: δ = 32.0–34.0, 27.5–29.5, 27.3 (s); after addition of *i*Pr$_2$NH (0.4 equiv based on Pd): δ = 27.5–29.5, 27.8 (s), 27.3 (s).
[8] For this experiment 4-Å MS powder was dried at 300 °C for 8 h under vacuum (< 0.05 Torr) to prevent contamination by water; otherwise, a lower deuterium content (55%) resulted. We thank Dr. Masahiro Terada for suggesting this procedure.
[9] The by-products were α-deuterated (to 70%) α-(trimethylsilylmethyl)tetralone (4%, 81% *ee*), α-hydroxy-α-methyltetralone (6%, 0% *ee*), and β-methyltetrahydro-α-naphthol (10%, 0% *ee*).
[10] Enantiomeric excesses were determined by HPLC on CHIRALCEL OD-H for **2b–e** and by capillary GLC on CP-chirasil-DEX CB for **2f** and **2g**. The configurations were assigned by comparing optical rotations with literature values: **2b**: M. Murata, M. Nakajima, K. Koga, *J. Chem. Soc. Chem. Commun.* **1990**, 1657–1658; **2c**: T. Yasukata, K. Koga, *Tetrahedron: Asymmetry* **1993**, *4*, 35–38; **2e**: G. Berti, B.Macchia, F. Macchia, L. Menti, *J. Chem. Soc. C* **1971**, 3371–3375; **2g**: A. I. Meyers, D. R. Williams, G. W. Erickson, S. White, M. Druelinger, *J. Am. Chem. Soc.* **1981**, *103*, 3081–3087. The configurations of **2d** and **2f**, though not yet determined, were assigned based on the similarity of the values.

Selective Enhancement of NMR Signals for α-Cyclodextrin with Laser-Polarized Xenon**

Yi-Qiao Song, Boyd M. Goodson, Rebecca E. Taylor, David D. Laws, Gil Navon, and Alexander Pines*

Xenon, hydrophobic and chemically inert, has been widely used as an NMR probe of chemical environments, both in solution and in the solid state.[1] With the application of optical pumping,[2] a large (>10%) ^{129}Xe nuclear-spin polarization can be generated. This polarization has been used to increase the sensitivity of ^{129}Xe NMR spectroscopy[3, 4] and magnetic resonance imaging (MRI),[5] and to supply polarization to neighboring spins on surfaces.[6] It was recently shown that enhanced xenon polarization can also be transferred to molecules in solution[7] by cross-relaxation, a process dubbed the *s*pin *p*olarization *i*nduced *n*uclear *O*verhauser *e*ffect (SPINOE). Because the SPINOE depends on the proximity of ^{129}Xe atoms to neighboring spins, as well as their relative motion, more rapid transfer of polarization is expected when xenon is temporarily bound, thereby permitting selective enhancement of NMR signals of nuclear spins near xenon binding sites.

Here we report polarization transfer from laser-polarized ^{129}Xe to ^{1}H spins in two molecular systems in solution: *p*-nitrotoluene (*p*-NT), which couples mainly diffusively to xenon, and α-cyclodextrin (α-CD, Figure 1), a cyclic oligosaccharide with a hydrophobic pocket known to bind xenon[8, 9] and other guest species.[10] Binding of xenon to α-CD gives rise to cross-relaxation rates up to 150 times greater than those between xenon and *p*-NT; this results in more rapid transfer of polarization. Furthermore, enhancements of ^{1}H spins adjacent to the xenon binding site in α-CD are greater than those of ^{1}H spins further away.

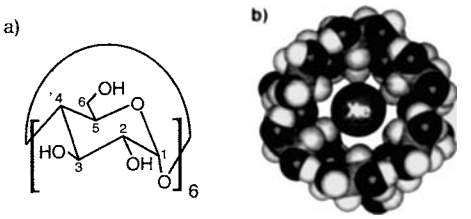

Figure 1. a) Structural formula of α-cyclodextrin. b) CPK model of α-cyclodextrin [16] in which a xenon atom is placed within the hydrophobic pocket containing the hydrogen atoms H3 and H5.

The change in the ^{1}H magnetization due to the presence of highly polarized xenon is well approximated by Equation (1).[7]

$$\frac{\Delta M^{H}}{M_{eq}^{H}} = -\sigma_n n^{Xe} T_1^{H} \frac{\gamma^{Xe}}{\gamma^{H}} \frac{\Delta M^{Xe}}{M_{eq}^{Xe}} (1-e^{-t/T_1^{H}}) \quad (1)$$

$$\sigma_n n^{Xe}, \quad \frac{1}{T_1^{Xe}} \ll \frac{1}{T_1^{H}} \quad (2)$$

Here, σ_n is the partial millimolar cross-relaxation rate, n^{Xe} is the concentration of ^{129}Xe in the solution, γ^{Xe}, γ^{H} are the magnetogyric ratios, M^{Xe}, M^{H} and M_{eq}^{Xe}, M_{eq}^{H} are the enhanced and equilibrium magnetization of ^{129}Xe and ^{1}H, respectively, T_1^{Xe}, T_1^{H} (under condition (2)) are the ^{129}Xe and ^{1}H spin-lattice relaxation times, and $\Delta M = M - M_{eq}$. In the absence of laser polarization, the ^{129}Xe–^{1}H NOE enhancement is minuscule ($\approx 10^{-5}$) due to low xenon concentration and weak ^{129}Xe–^{1}H coupling. In previous work[9, 11] ^{129}Xe–^{1}H interactions were indirectly observed by detecting changes in the xenon signal during proton saturation. With the use of laser-polarized xenon, however, the ^{129}Xe–^{1}H NOE enhancement ($\approx 10^{-2}$)[12] is detected directly in the resolved ^{1}H NMR spectrum.

The technique used for optically pumping xenon has been described elsewhere;[4] ^{129}Xe polarizations are typically 5–10%. To detect the SPINOE signals, we used a heteronuclear difference NOE pulse sequence (Figure 2), which suppresses the equilibrium ^{1}H magnetization and is therefore directly sensitive to the SPINOE. The ^{1}H SPINOE NMR spectra for 0.1 M *p*-NT in [D$_6$]benzene with laser-polarized xenon are shown in Figure 3. Equation (1) was used to determine values of σ_n for *p*-NT by assuming a linear dependence of the cross-relaxation rate on the concentration of polarized xenon (Table 1). The values are similar to that for the hydrogen atom of [D$_5$]benzene, which is in agreement with a rough theoretical

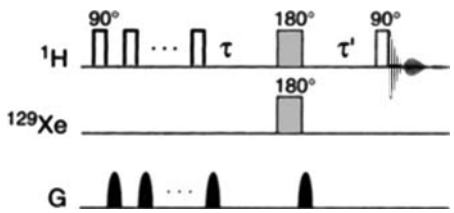

Figure 2. Heteronuclear difference NOE pulse sequence for ^{129}Xe–^{1}H SPINOE NMR spectroscopy based on sequences developed by Shaka [13]. The equilibrium ^{1}H NMR signal is saturated by 90° and gradient pulses (G); the saturation is maintained by a 180° pulse followed immediately by a gradient pulse. A xenon 180° pulse allows SPINOE signals to accumulate during the mixing periods τ and τ'. Each spectrum represents the difference of two scans.

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[**] We thank A. J. Shaka and M. Luhmer for helpful comments and suggestions. D. D. L. gratefully acknowledges the Howard Hughes Medical Institute for a pre-doctoral fellowship. G. N. is Visiting Miller Research Professor at the University of California, Berkeley. This work was supported by the Office of Basic Sciences, Materials Sciences Division of the U. S. Deptartment of Energy (contract no. DE AC03-76SF00098).

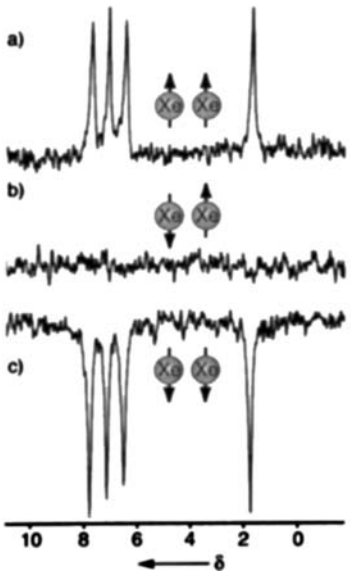

Figure 3. ^{1}H SPINOE NMR spectra of 0.1 M *p*-nitrotoluene in [D_6]benzene ($\tau = 4.5$ s and $\tau' = 3.5$ s). Chemical shifts are referenced to the signal for [D_5]benzene ($\delta = 7.16$). a) Spectrum acquired with the pulse sequence in Figure 2 after introduction of negatively polarized ^{129}Xe (with xenon spins "up", $\gamma^{Xe} < 0$); b) as in a), but in the absence of a xenon 180° pulse; c) spectrum acquired after introduction of positively polarized ^{129}Xe (prepared by inverting the magnetic field in which the ^{129}Xe is laser-polarized); this results in a sign change in the spectrum.

Table 1. ^{129}Xe–^{1}H cross-relaxation rates σ_n and ^{1}H spin-lattice relaxation times T_1

Molecule	Proton	σ_n [10^{-6} s^{-1} mM^{-1}]	T_1 [s] [a]
p-NT	CH_3	0.025 ± 0.007	6.8
	H3, H5	0.032 ± 0.006	35
	H2, H6	0.029 ± 0.005	23
[D_5]benzene [b]	H	0.028 ± 0.007	110
α-CD	H1	0.44 ± 0.14	1.1
	H2	1.3 ± 0.5	1.1
	H3	4.1 ± 0.8	1.2
	H4	1.6 ± 0.3	1.1
	H5	4.9 ± 1.2	0.87
	H6	1.2 ± 0.4	0.78
	OH(2)	0.70 ± 0.22	1.2
	OH(3)	0.86 ± 0.18	1.0
	OH(6)	0.36 ± 0.14	1.1

[a] The error range for the T_1 measurements is about ±5%. [b] Data for [D_5]benzene signals in the *p*-NT spectra.

estimate of the cross-relaxation rate based on dipolar coupling modulated by molecular diffusion.[7]

The first indication of stronger couplings for laser-polarized xenon in α-CD is the reduced ^{129}Xe relaxation time T_1 (≈20 s in 0.1 M α-CD/[D_6]DMSO), which is short compared to that for xenon in 0.1 M *p*-NT/[D_6]benzene (>500 s). The equilibrium ^{1}H NMR spectrum of α-CD is shown in Figure 4a; the chemical shifts were assigned by means of a 2D COSY spectrum. After introduction of laser-polarized ^{129}Xe into the solution, SPINOE NMR spectra (Figure 4b–d) were obtained by using the pulse sequence of Figure 2. Values of σ_n for the ^{1}H spins in α-CD were obtained by fitting the data to Equation (1) (Table 1). The increase in couplings between xenon and α-CD arising from xenon binding[14] demonstrates the sensitivity of σ_n to the binding of xenon with molecules in solution.

In the case of α-CD, variation of signal enhancements is observed in the ^{1}H NMR spectrum: The strongest SPINOEs are observed from the H3 and H5 atoms located inside the hydrophobic pocket. Differences in the xenon coupling to various protons is expected when binding occurs, because dipolar relaxation is sensitive to the distances between spins and varies as $\sigma_n \propto r^{-6}$.[15] For example, from this relationship a ratio of 1:1.5 can be estimated for the range of relative distances between Xe–H5 and Xe–H1, neglecting transferred NOEs.[17] According to the X-ray structure of α-CD,[16] a ratio between 1:1.2 and 1:2, corresponding to Xe–H5 distances of about 3 to 6 Å and Xe–H1 distances of about 6 to 8 Å, is consistent with a distribution of xenon locations within the hydrophobic pocket.

These results show the potential of ^{129}Xe–^{1}H SPINOE experiments for probing the structure and dynamics of molecules in solution. Furthermore, they may have implications for NMR studies of hydrophobic potentials in systems involved in hydrophobic binding, for example, inclusion compounds, membranes, and proteins.

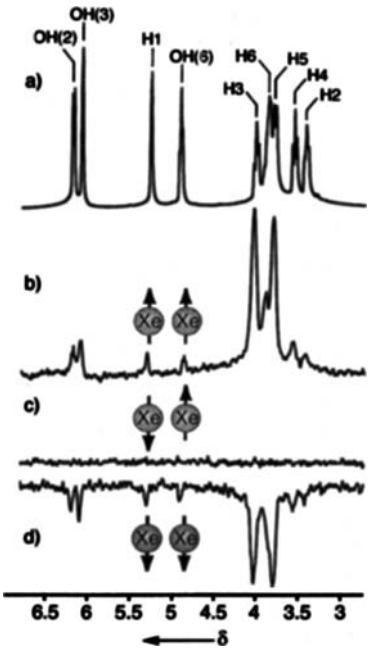

Figure 4. a) ^{1}H NMR spectrum of 0.05 M dehydrated α-cyclodextrin in [D_6]DMSO; b) ^{1}H SPINOE NMR spectrum of α-CD acquired with the pulse sequence in Figure 2 after introduction of negatively polarized ^{129}Xe; c) as in b), but in the absence of a xenon 180° pulse; d) ^{1}H SPINOE NMR spectrum acquired after introduction of positively polarized ^{129}Xe; b)–d) $\tau = 0.63$ s and $\tau' = 0.37$ s.

Received: June 16, 1997 [Z 19560 IE]
German version: *Angew. Chem.* **1997**, *109*, 2464–2466

Keywords: cyclodextrins · host–guest chemistry · laser polarization · NMR spectroscopy · xenon

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Reducible Nanoscale Molecular Rods Based on Diacetylene-Linked Poly(phenylthio)-Substituted Benzenes**

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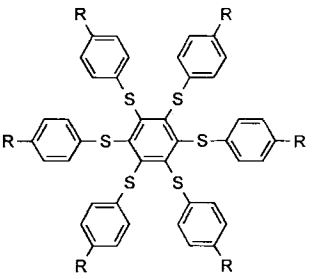
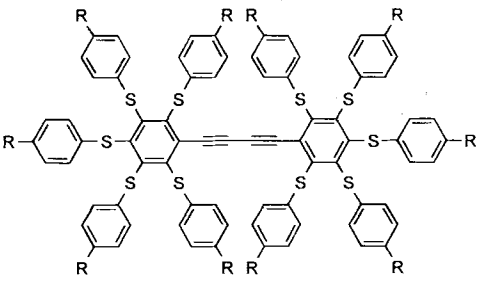
Structures of defined geometry and nanometric size containing electron-accepting subunits are of much interest as reducible molecular wires for the development of molecular and supramolecular electronic and photonic devices.[1–3] They may serve as connectors between components, and also possess marked nonlinear optical properties due to extended π conjugation.[4] Whereas the very actively studied entities built from conjugated electron-rich groups (such as thiophene, pyrrole[5]) lead to electronic conduction upon oxidation (p-doping), reducible wires are susceptible to n-doping through reduction and may show higher electronic mobility.

Molecular wires based on pyridinium end groups and carotenoid-type conjugated chains (termed caroviologens), which we investigated earlier, induce electron transport through lipid membranes.[5] Poly(phenylthio) aromatic systems such as **1** are well known for their host–guest chemistry in the solid state[6] and also display remarkably low reduction potentials.[7] They thus appeared to be promising candidates for incorporation into conjugated systems chosen for the development of novel types of reducible molecular wires.

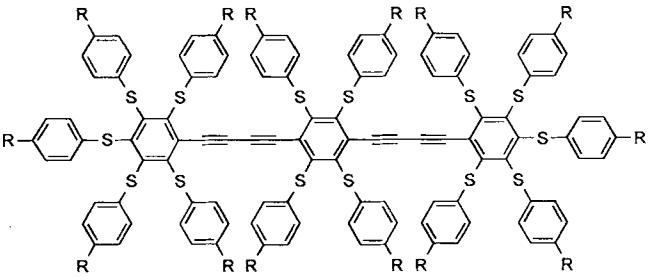
We present here the synthesis, the structural characterization and some physicochemical properties of **2** and **3**, in which two



1a, R=H
1b, R=*t*Bu

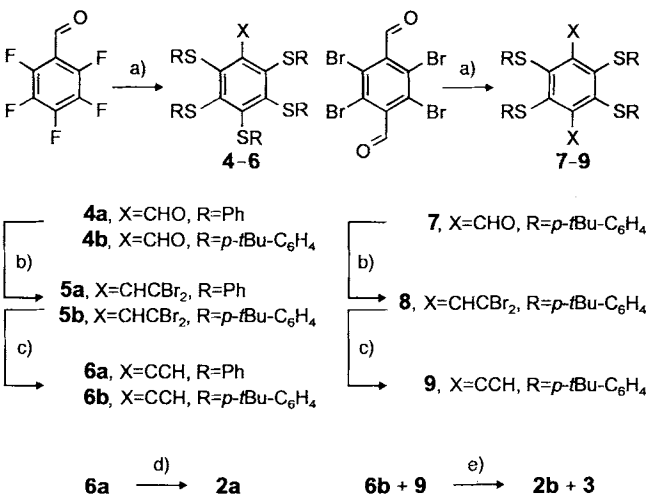


2a, R=H
2b, R=*t*Bu



3, R=*t*Bu

and three poly(phenylthio)benzene subunits are linked by diacetylene bridges as efficient π-conjugation connectors. Starting from the corresponding halogenated benzaldehydes, the acetylene-functionalized phenylthio-substituted benzenes were synthesized in three steps (Scheme 1). Aromatic nucleophilic



Scheme 1. Synthesis of **2** and **3**. a) DMI, NaSR, RT; b) CBr_4, PPh_3, CH_2Cl_2, RT; c) LDA, THF, −78 °C, H_2O; d) $Cu(OAc)_2$, pyridine, 45 °C; e) CuCl, TMEDA, O_2, $CHCl_3$, RT.

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[**] Supported by the CNRS (URA 422), the Swiss National Science Foundation, the Collège de France (postdoctoral fellowship to M. M.), and the Deutsche Forschungsgemeinschaft (postdoctoral fellowship to K. M. F.).

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