Conformational Studies of Substituted Dibenzo-14-Crown-4 Ethers: a 1-D and 2-D ¹H and ¹³C NMR Investigation†

Zhihong Chen and Richard A. Sachleben*
Chemistry Division, Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831-6119, USA

The solution structures of substituted dibenzo-14-crown-4 ethers have been investigated by one- and two-dimensional NMR methods (proton vicinal coupling constants, ¹³C chemical shifts and ROESY). The preferred conformations in solution for substituents on *sym*-dibenzo-14-crown-4 ethers have been shown to depend on the atom (carbon or oxygen) linking the substituent to the crown ring. Substituents attached by a carbon linkage, including methyl, 2-hydroxyethyl and carboxymethyl, prefer a pseudo-equatorial conformation, *i.e.* with the substitutent oriented *anti* to the ring C–O bond. Substituents attached by an oxygen linkage, including hydroxy, methoxy, and carboxymethoxy, prefer the pseudo-axial (*gauche*) conformation.

In the design and synthesis of cation-selective ligands, the 14-crown-4 system is of interest due to its nearly optimal cavity size for complexation of the lithium cation. Studies have shown that the binding strengths of substituted 14-crown-4 ethers are influenced by the structure of substituent groups and their position on the crown ring.[1–7] The dibenzo-14-crown-4 ligand system has been shown to be highly preorganized for the complexation of Li⁺,[8,9] and a number of *sym*-dibenzo-14-crown-4 lariat ethers bearing proton-ionizable sidearms have been studied for the selective complexation and extraction of lithium.[10–13] It has been proposed that the orientation of the ionizable sidearm in these lariat ethers, relative to the crown cavity, affects the extraction properties of these crowns.[14] However, few studies have addressed the question of which orientations are actually adopted by lariat ethers in solution.

Structural studies by X-ray diffraction methods of substituted dibenzo-14-crown-4 ethers and their complexes in the solid state[9,15–19] have indicated that the conformation adopted by the sidearm is determined by the type of linkage between the sidearm and the ring. Although determination of crystal structures is the most secure method for obtaining structural information, the method is not suitable for the analysis of conformational preferences in solution because static representations of molecular structure are obtained in which crystal packing forces may determine the conformational preferences. While in most cases the conformations of molecules have been found to be very similar both in solution and in the solid state, conformational differences between the crystalline and the solution state are often observed for polar molecules which interact strongly with their surroundings (hydrogen-bonding, solvation, association, *etc.*).[20]

NMR spectroscopy offers many advantages for studying conformations of molecules in solution. Among the various NMR techniques, one-dimensional chemical shifts (¹H and/or ¹³C), coupling constants, and ¹H–¹H nuclear Overhauser effects (NOE) have been widely employed for conformational studies.[21] However, because *J*-coupling and NOE measurements require that resonances be well enough resolved to permit selective irradiation, 2-D methods such as NOESY (nuclear Overhauser enhancement spectroscopy)[22] and ROESY (rotating frame Overhauser effect spectroscopy)[23] have been utilized for studying molecular structure in solution.

ROESY is similar to NOESY, but less sensitive to the cross-relaxation rate on the correlation time of the molecular motion in solution. In contrast to the NOE, the ROE is always positive (negative cross signals with respect to the diagonals), and ROE build-up rates are greater than NOE rates, so that the ROESY signal is stronger than the corresponding NOESY signal for small and intermediate size molecules.

The goal of this study was to determine the conformational preferences of dibenzo-14-crown-4 lariat ethers in solution, leading to an understanding of the state of preorganization of the free ligand for metal ion complexation. The solution structures of a series of substituted dibenzo-14-crown-4 compounds (1–9 in Fig. 1) with different sidearms were determined using both one- and two-dimensional NMR techniques. The results permit, for the first time, definite conclusions regarding the pseudo-axial *versus* pseudo-equatorial configuration of the sidearm in this series of compounds in solution.[24]
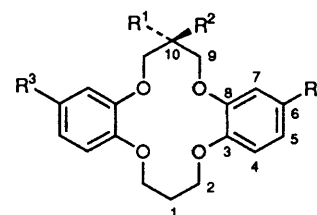
1 R¹ = R² = R³ = H

2 R¹ = $\overset{11}{C}H_3$, R² = R³ = H

3 R¹ = $\overset{11}{C}H_2\overset{12}{C}H_2OH$, R² = R³ = H

4 R¹ = $\overset{11}{C}H_2\overset{12}{C}O_2H$, R² = R³ = H

5 R¹ = $\overset{11}{C}H_2\overset{12}{C}O_2H$, R² = H, R³ = $C(\overset{13}{C}\overset{14}{H_3})_2\overset{15}{C}H_2\overset{16}{C}(\overset{17}{C}H_3)_3$

6 R¹ = H, R² = OH, R³ = H

7 R¹ = H, R² = $O\overset{11}{C}H_3$, R³ = H

8 R¹ = H, R² = $O\overset{11}{C}H_2\overset{12}{C}H_2OH$, R³ = H

9 R¹ = H, R² = $O\overset{11}{C}H_2\overset{12}{C}O_2H$, R³ = $C(\overset{13}{C}\overset{14}{H_3})_2\overset{15}{C}H_2\overset{16}{C}(\overset{17}{C}H_3)_3$

Fig. 1 Structures of substituted dibenzo-14-crown-4 ethers with the numbering scheme employed
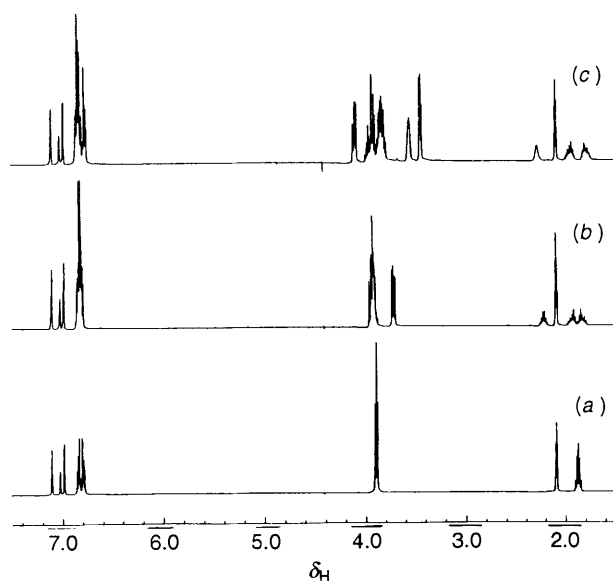
Fig. 2 400 MHz proton spectra of 1 (a), 2 (b) and 8 (c) in [$^2H_8$]toluene

(b)

Scheme 1 Conformations of substituted 14-crown-4 ethers

Results and Discussion

Unsubstituted Dibenzo-14-Crown-4 (1).—1 Has the simplest spectrum of the cyclic ethers studied here.* Its ^1H NMR spectrum [Fig. 2(a)] consists of a quintet at δ 1.87 (1-H), a triplet in the ether region at δ 3.89 (2-H), and a multiplet due to the aromatic protons around δ 6.8. A similar pattern of equivalence is observed in the decoupled ^{13}C spectrum, where only five peaks are observed at room temperature. Low temperature experiments, performed on 1 by cooling the sample in 10 °C increments to −90 °C, showed no additional peaks in either the ^1H or the ^{13}C spectra. Only slight proton line broadening was observed at the lowest temperatures. Both X-ray and molecular mechanics studies have shown that in the lowest energy conformation, 1 adopts a wedge shape where the bridge propylene units are in a pseudo-boat conformation.[9,15–18] Therefore, the observed ^1H and ^{13}C spectra are consistent with a rapid interconversion on the NMR timescale between two equivalent wedge-shaped conformations (see Scheme 1).

sym-Dibenzo-14-crown-4 (2–9).—In contrast to 1, the ^1H spectra of compounds 2–9 were more complicated. The 400 MHz proton spectra of 2–9 were partially assignable by simple inspection. COSY and TOCSY were performed as necessary to complete the assignments. The complete ^{13}C assignments were then made using DEPT and HETCOR.[25] Representative proton spectra (for 2 and 8) are shown in Fig. 2(b) and (c). As expected, the protons on C-2 and -9 or on C-1 and -10 are no longer equivalent. In addition, the two protons on C-1 are not equivalent and appear as two multiplets separated by δ 0.1; a similar non-equivalence is found for the pairs of protons on C-2 and on -9, although these resonances are not always as well separated as are the resonances for the protons on C-1. Integration of the ^1H spectra shows that the methine resonance, 10-H, corresponds to one proton, as does each of the resonances for the protons on C-1. For the spectra where the two pairs of signals for protons on C-2 and -9 can be resolved, the integrals indicate two protons per resonance. In the ^{13}C spectra for 2–9 (not shown), ten carbon signals were detected for the carbons of the macrocyclic ring, C-1–C-10, indicating a symmetry across the molecule along a line or plane through C-1 and -10.

* Please note the non-standard numbering scheme employed in this work (Fig. 1).
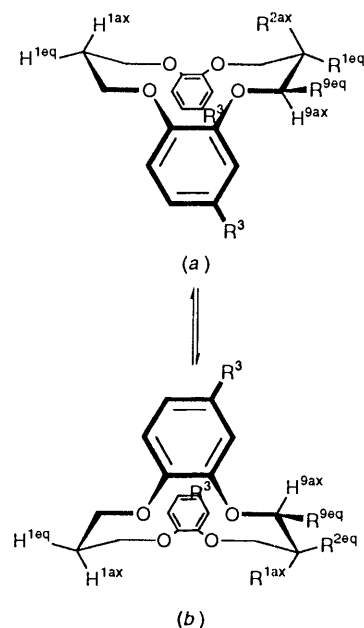
Variable temperature NMR spectra of 2–9 show little change over the temperature range −90 ⩽ T ⩽ 50 °C. The lack of additional signals or significant line broadening in either the ^1H or ^{13}C spectra at low temperature, or signal averaging at high temperature, indicates that no conformational inter-conversion occurs over the temperature range studied, in contrast to the results for the unsubstituted crown 1.
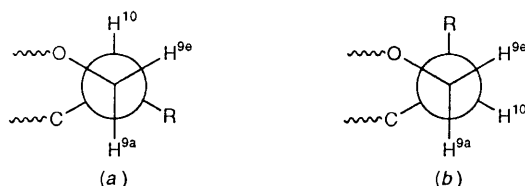
We interpret these results in terms of a wedge-shaped conformation similar to that found in the structures determined by X-ray diffraction, with a plane of symmetry bisecting the molecule through C-1 and -10. The two resonances for the two protons on C-1 can be rationalized in terms of the hydrogens occupying pseudo-axial and pseudo-equatorial positions; a similar argument explains the non-equivalence of the protons on C-2 and also on -9. The variable temperature results indicate that a single conformation, either (a) or (b) of Scheme 1 is preferred for each of 2–9, where the substituent group occupies exclusively either a pseudo-axial (*gauche* to the C-9-O bond) or pseudo-equatorial (*trans* to the C-9-O bond) position. Determination of the conformational preferences of the sidearms in 2–9 can then be made, with the most definitive data being the proton coupling constants and the NOE measurements.

Proton Vicinal Coupling Constants.—Proton vicinal coupling constants have been related to the torsion angle between the coupled protons *via* the Karplus equation.[26] Studies have also shown that the magnitude of coupling constants depends on a variety of other molecular parameters, such as substitution, bond angle, bond length, and the electronegativity and relative position of substituents attached to the H-C-C-H fragment. Typical values of vicinal H-H coupling constants in conformationally restrained systems such as cyclohexane are 6–14, 3–5 and 0–5 Hz for ax–ax, ax–eq and eq–eq protons, respectively (ax = axial, eq = equatorial).[21]

Newman projections along C-9 and -10 of substituted dibenzo-14-crown-4 are shown in Fig. 3 for the two cases where the sidearm is equatorial (a) and axial (b). The methylenes are assumed to be staggered with the sidearm, but 60° dihedral angles are only convenient approximations. In the conformer (a), the equatorial sidearm requires an axial methine proton. Because of the staggered orientation assumed for the oxy-

Table 1 ^{1}H NMR vicinal coupling constants of substituted sym-dibenzo-14-crown-4 ethers at 303 K (Hz)

Compound	R^{1}	J_{10-9a}	J_{10-9e}	Solvent
2	CH$_3$	7.1	5.1	[^{2}H$_8$]Toluene
		7.1	4.9	[^{2}H$_6$]Acetone
3	CH$_2$CH$_2$OH	6.6	4.8	[^{2}H$_8$]Toluene
6	OH	3.9	3.9	[^{2}H$_6$]Acetone
		3.5	3.5	CDCl$_3$
7	OCH$_3$	4.8	4.8	CDCl$_3$
8	OCH$_2$CH$_2$OH	5.7	5.7	[^{2}H$_6$]Acetone
9	OCH$_2$CO$_2$H	5.4	5.4	[^{2}H$_8$]Toluene
		5.4	5.4	[^{2}H$_6$]Acetone

Fig. 3 Newman projections along C-9 and -10 of substituted dibenzo-14-crown-4 ethers

Table 2 Dipolar proton coupling observed in the 2-D ROESY spectra of sym-dibenzo-14-crown-4 ethers in [^{2}H$_8$]toluene at 303 K

Compound	Resonance	Obsd. ROE cross-peaks^a
2	11-H	9e-H(s), 9a-H(s), 10-H(s)
	10-H	9e-H(i), 11-H(s)
	9e-H	9a-H(s), 10-H(i), 11-H(s)
	9a-H	9e-H(s), 11-H(s)
3	12-H	11-H(s), 9a-H(w)
	11-H	12-H(s), 10-H(s), 9e-H(s), 9a-H(s)
	10-H	11-H(s), 9e-H(i)
	9e-H	9a-H(s), 10-H(i), 11-H(s)
	9a-H	9e-H(s), 11-H(s), 12-H(w)
7	11-H	9e-H(w), 10-H(w)
	10-H	9e-H(s), 9a-H(s), 11-H(w)
	9e-H	9a-H(s), 10-H(s), 11-H(w)
	9a-H	9e-H(s), 10-H(s)
8	12-H	11-H(i)
	11-H	9e-H(i),10-H(i), 12-H(i)
	10-H	9e-H(s), 9a-H(s), 11-H(i)
	9e-H	9a-H(s), 10-H(s), 11-H(i)
	9a-H	9e-H(s), 10-H(s)

^{a} Intensities of ROE cross peaks were obtained qualitatively: s, strong; i, intermediate; w, weak.

propylene sub-units, the methine proton 10-H has a trans-diaxial relationship with one of the methylene protons, 9a-H, which should be reflected in the magnitude of the coupling constant; a larger coupling constant is expected for 10-H–9a-H than for 10-H–9e-H. Conversely, in conformer (b), a gauche relationship exists between the methine proton and both neighbouring methylene protons, which should be reflected in two small and equal vicinal coupling constants, $J_{10-9a} = J_{10-9e}$.

As is clearly shown from the proton coupling patterns [Fig. 2(b), (c)], the multiplets for 1-H and for 2-H are characteristic of four-spin AA'BB' coupled systems. Furthermore, the two quartets of 9a-H and 9e-H are well enough resolved to allow determination of their coupling constants by direct inspection of the 1-D spectra. The geminal coupling constant J_{9a-9e} was assigned from the coupling pattern of 9a-H and 9e-H, and confirmed by 1-D homonuclear decoupling experiments. The experimentally determined coupling constants for 2, 3 and 6–9 are given in Table 1. For compounds 2 and 3, the vicinal coupling constant values J_{10-9a} are about 2 Hz larger than J_{10-9e} values, leading to the assignment of an axial conformation for proton 10-H. On the other hand, two small vicinal coupling constants with the same magnitude were obtained for compounds 6–9. It is reasonable to interpret these results in terms of the proton 10-H in 6–9 occupying the equatorial position, where the torsion angles are approximately the same. Protons rapidly interchanging between the axial and equatorial positions would be expected to give averaged vicinal coupling constants, as has been observed for certain crown ethers.[27] Clearly, this is not the case for the compounds 2–9, (vide supra). The relatively small anti–anti vicinal coupling constants are probably due to substituent effects.

NOE Results.—Examination of the two conformations in Fig. 3 leads to the following predictions. In conformer (a), NOEs are expected between protons on the sidearm and both 9-H protons, whereas the trans-diaxial orientation of the methine proton 10-H and the proton 9a-H would appear to make the distance between these protons too great to produce a measurable NOE between them. Therefore, only the NOE between 10-H and 9e-H is expected. Conversely, in conformer (b), protons on the axial sidearm are expected to show an NOE only to 9e-H, while 10-H should show NOEs to both 9e-H and

9a-H. 2-D ROESY experiments were performed on compounds 2, 3, 7 and 8; the results are listed in Table 2.

The NOE experiments performed on 2 and 3 showed strong cross peaks between the sidearm protons and both methylene protons 9a-H and 9e-H, consistent with a solution structure corresponding to conformation (a), i.e., the sidearm is in the pseudo-equatorial position relative to the crown ring. Furthermore, for the methine resonance, no cross peak appeared between 10-H and 9a-H. On the other hand, in 7 and 8, crosspeaks were observed between 10-H and both 9a-H and 9e-H, as well as between the sidearm protons and 9e-H; no cross peak appeared between the sidearm protons and 9a-H. These results support the assignment of conformation (b) to 7 and 8; the sidearm prefers the pseudo-axial position in these compounds.

^{13}C *Chemical Shifts.*—The similarity between the conformation of the oxypropylene bridge of dibenzo-14-crown-4 and the chair form of cyclohexane and 1,3-dioxane led us to compare the ^{13}C chemical shifts of sym-dibenzo-14-crown-4 ethers with those of substituted cyclohexanes. In general, ^{13}C chemical shifts are sensitive to molecular conformation. In cyclohexanes, the chemical shift of a carbon having an axial substituent occurs at higher field than the chemical shift of the corresponding carbon bearing an equatorial substituent, due to gauche interactions between the substituent on the α-carbon and the β-carbon of the ring.[28] It has also been shown that the substituent–shift correlation for the cyclohexanes and the 1,3-dioxanes are generally comparable but may differ in magnitude.[29] We have found that despite the differences in the overall ring structure between cyclohexane and dibenzo-14-crown-4, a similar correlation between ^{13}C chemical shift and substituent position can be made.

The chemical shift differences of the α-carbon of substituted cyclohexanes in different conformations and of C-10 of substituted dibenzo-14-crown-4 ethers are given in Table 3. The ^{13}C chemical shift differences observed for C-10 bearing a carbon linkage are similar to the ^{13}C shift difference found for the equatorial methylcyclohexane. Alternatively, the ^{13}C chemical shifts observed for C-10 bearing an oxygen linkage correlate closely with corresponding cyclohexanes with substituents in the axial position. These results are consistent with the conformational assignments obtained from the

Table 3 ^{13}C NMR substituent shift correlations for substituted cyclohexanes and dibenzo-14-crown-4 lariat ethers

Compound	Solvent	Cyclohexane[a] ax	Cyclohexane[a] eq	Dibenzo-14-crown-4[b]
2	CDCl$_3$	1.5	6.0	4.5
	[^{2}H$_6$]Acetone			4.5
	[^{2}H$_8$]Toluene			4.3
3	CDCl$_3$			6.6
	[^{2}H$_6$]Acetone			6.9
	[^{2}H$_8$]Toluene			7.2
4	CDCl$_3$			6.5
	[^{2}H$_6$]Acetone			6.9
5	CDCl$_3$			5.9
	[^{2}H$_6$]Acetone			6.6
	[^{2}H$_8$]Toluene			6.4
6	CDCl$_3$	39.0	43.0	38.6
	[^{2}H$_6$]Acetone			39.4
	[^{2}H$_8$]Toluene			39.2
7	CDCl$_3$	47.0	52.0	48.0
	[^{2}H$_6$]Acetone			48.9
	[^{2}H$_8$]Toluene			48.9
8	CDCl$_3$			48.1
	[^{2}H$_6$]Acetone			47.7
	[^{2}H$_8$]Toluene			47.8
9	CDCl$_3$	46.0	52.0	48.5
	[^{2}H$_6$]Acetone			48.1
	[^{2}H$_8$]Toluene			49.1

[a] δ from unsubstituted cyclohexane. [b] δ from the dibenzo-14-crown-4.

coupling constant and NOE results and thus provide a useful tool for surveying the conformations of these compounds.

Definite conformational preferences are observed for substituted dibenzo-14-crown-4 ethers. While the parent compound **1** undergoes a rapid conformational interconversion in solution, the substituted crowns **2–9** are more rigid and adopt conformations in which the orientation of the sidearm relative to the macrocyclic ring depends on the linkage of the sidearm to the ring. Compounds **2–5**, in which the sidearm is attached to the crown ring through a carbon linkage, show a marked preference for the conformation in which the sidearm adopts a pseudo-equatorial position. Alternatively, in compounds **6–9**, in which attachment of the sidearm occurs through an ether linkage, the pseudo-axial conformer is preferred. The conformational preferences of mono-substituted cyclohexanes and 1,3-dioxanes carrying substituents at the 5 position have been shown to be sensitive to dipolar, hydrogen-bonding and steric effects.[30] Similar effects may be operating in the substituted dibenzo-14-crown-4 system. As can be seen in Fig. 2, two *gauche* interactions exist when the sidearm adopts a pseudo-axial position [conformer (*b*)], whereas only one *gauche* interaction is present in the pseudo-equatorial conformer [conformer (*a*)]. Therefore, the preferred sidearm position in the relatively rigid, substituted dibenzo-14-crown-4 system may be the pseudo-equatorial position, as is observed for **2–5**. When the linkage changes from carbon to oxygen, the preference changes to the pseudo-axial position. This may be a result of the reduced steric requirements of the ether group compared to a methylene, or as a result of an unfavourable dipolar interaction between the macrocyclic ethers and the sidearm oxygen. It has been suggested that intramolecular hydrogen-bonding between OH groups and the ring oxygens in the substituted 1,3-dioxane and dibenzo-16-crown-5 systems is responsible for the observation of a preference for the axial position in these compounds.[31] While this effect may be present in **6**, **8** and **9**, hydrogen-bonding cannot account for the axial preference shown by **7**. We are currently investigating related lariat ether systems to determine if the observations reported here are of a general nature or limited to the present system.

Experimental

The preparations of compounds **1–6**, **8** and **9** have been reported elsewhere. Compound **7** was prepared by methylation (dimethyl sulfate–NaH–THF) of **6**. [^{2}H$_6$]Acetone (99.9%) and [^{2}H$_8$]toluene (99.6%) were purchased from Cambridge Isotope Laboratory. CDCl$_3$ (99.8%) was purchased from Aldrich Chemical Company. Solvents were dried over molecular sieves before use.

All NMR experiments were performed on 100 mmol dm^{-3} solutions of the crown ethers in [^{2}H]chloroform, [^{2}H$_6$]acetone or [^{2}H$_8$]toluene in 5 mm tubes on a Bruker MSL-400. Chemical shifts were referenced to tetramethylsilane. All experiments, except the variable temperature experiments, were conducted at 303 K. 1-D ^{1}H NMR spectra were obtained at 400.13 MHz using a spectral width of 4000 Hz over 32 K data points. 1-D ^{13}C spectra were obtained at 100.613 MHz using a spectral width of 20 kHz over 32 K data points.

Two-dimensional rotating-frame NOE (ROESY)[22] spectra were recorded in the phase-sensitive mode (TPPI) using the sequence –RD–$\pi/2$–t_1–CW(spin lock)–t_2–. A mixing time of 500 ms was used. A total of 256 FIDs of 16 scans each (4 dummy scans) were collected. The spectral width was 3400 Hz. A squared sine-bell function shifted by $\pi/3$ was applied for processing both in the t_1 and t_2 dimensions. The data matrix was expanded to a 1K × 1K data file before Fourier transformation.

References

1 Y. Kudo, Y. Takeda, K. Hiratani and H. Matsuda, *Anal. Sci.*, 1991, **7**, 549.

2 R. Kataky, P. E. Nicholson and D. Parker, *J. Chem. Soc., Perkin Trans. 2*, 1990, 321.

3 K. Kimura, S. Iketani, H. Sakamoto and T. Shono, *Analyst*, 1990, 115, 1251.

4 Y. Nakatsuji, R. Wakita, Y. Harada and M. Okahara, *J. Org. Chem.*, 1989, 54, 2988.

5 H. Sakamoto, K. Kimura, M. Tanaka and T. Shono, *Bull. Chem. Soc. Jpn.*, 1989, 62, 3394.

6 E. Uhlemann, H. Bukowsky, F. Dietrich, K. Gloe, P. Muhl and H. Mosler, *Anal. Chim. Acta*, 1989, 224, 47.

7 K. Wilcox and G. E. Pacey, *Talanta*, 1991, 38, 1315.

8 R. A. Sachleben and J. H. Burns, *J. Chem. Soc., Perkin Trans. 2*, 1992, 1971.

9 N. K. Dalley, W. M. Jiang and U. Olsher, *J. Inclusion Phenomena*, 1992, 12, 305.

10 G. Shoham, D. W. Christianson, R A. Bartsch, G. S. Heo, U. Olsher and W. N. Lipscomb, *J. Am. Chem. Soc.*, 1984, 106, 1280.

11 U. Olsher, F. Frolow, R. A. Bartsch, M. J. Pugia and G. Shoham, *J. Am. Chem. Soc.*, 1989, 111, 9217.

12 R. A. Bartsch, B. P. Czech, S. I. Kang, L. E. Stewart, W. Walkowiak, W. A. Charewicz, G. S. Heo and B. Son, *J. Am. Chem. Soc.*, 1985, 107, 4997.

13 Y. Habata, M. Ikeda and S. Akabori, *Tetrahedron Lett.*, 1992, 33, 3157.

14 R. A. Bartsch, *Solv. Extr. Ion Exch.*, 1989, 7, 829.

15 J. H. Burns and R. A. Sachleben, *Inorg. Chem.*, 1988, 27, 1787.

16 J. H. Burns and R. A. Sachleben, *Inorg. Chem.*, 1990, 29, 788.

17 J. H. Burns and R. A. Sachleben, *Acta Crystallogr., Sect. C, Cryst. Struct. Commun.*, 1991, 47, 2339.

18 R. A. Sachleben and J. H. Burns, *Acta Crystallogr., Sect. C, Cryst. Struct. Commun.*, 1991, 47, 1968.

19 U. Olsher, F. Frolow, N. K. Dalley, J. Weiming, Z.-Y. Yu, J. M.

Knobeloch and R. A. Bartsch, *J. Am. Chem. Soc.*, 1991, 113, 6750.

20 H. Kesler, G. Zimmermann, H. Forster, J. Engel, G. Oepen and W. S. Sheldrick, *Angew. Chem., Int. Ed. Engl.*, 1981, 20, 1053.

21 H. Friebolin, *Basic One- and Two-Dimensional NMR Spectroscopy*, VHC, New York, 1991.

22 J. Jeener, B. H. Meier, P. Bachmann and R. R. Ernst, *J. Chem. Phys.*, 1979, 71, 4566.

23 A. Bax and D. G. Davis, *J. Magn. Reson.*, 1985, 63, 207.

24 A preliminary communication of this work has been accepted for publication: Z.-H. Chen and R. A. Sachleben, *J. Inclusion Phenomena*, in the press.

25 Z.-H. Chen and R. A. Sachleben, *Magn. Reson. Chem.*, in the press.

26 R. J. Abraham and G. Gatti, *J. Chem. Soc. B*, 1969, 961.

27 (a) D. Live and S. I. Chan, *J. Am. Chem. Soc.*, 1976, 98, 3769; (b) J. F. Lewison, R. G. Ghiradelli and R. A. Palmer, *Inorg. Chem.*, 1989, 28, 3909.

28 H. Schneider and V. Hoppen, *Tetrahedron Lett.*, 1974, 579.

29 A. J. Jones, E. L. Eliel, D. M. Grant, M. C. Knoeber and W. F. Bailey, *J. Am. Chem. Soc.*, 1971, 93, 4772.

30 (a) E. L. Eliel, *Angew. Chem., Int. Ed. Engl.*, 1972, 11, 739; (b) D. K. Dalling and D. M. Grant, *J. Am. Chem. Soc.*, 1967, 89, 6612.

31 (a) E. L. Eliel and M. C. Knoeber, Sr., *J. Am. Chem. Soc.*, 1968, 90, 3444; (b) N. Baggeet, M. A. Bukhari, A. B. Foster, L. Lehmann and J. M. Webber, *J. Chem. Soc.*, 1963, 4157; (c) M. J. Pujia, B. E. Knudsea, C. V. Cason and R. A. Bartsch, *J. Org. Chem.*, 1987, 52, 541.