Registry No. Li, 7439-93-2; $LiBH_2$, 64360-74-3; $LiCH_3$, 917-54-4; $LiNH_2$, 7782-89-0; LiOH, 1310-65-2; LiF, 7789-24-4; $(Li_2)_2$, 12596-49-5; $(LiBH_2)_2$, 88656-95-5; $(LiCH_3)_2$, 33825-29-5; $(LiNH_2)_2$, 88656-96-6; $(LiOH)_2$, 54251-08-0; $(LiF)_2$, 12265-82-6.

Studies of Inclusion Complexes of Cycloamyloses in the Solid State by NMR Methods

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Although previous studies[1,2] of inclusion complexes of the Schardinger dextrins (otherwise known as cyclodextrins or cycloamyloses) using NMR methods have provided valuable insight, those studies have been confined to soluble complexes. Prompted by the rapidly growing interest in the use of modified cycloamyloses as model enzymes,[3-6] and also by commercial use of solid cycloamyloses to sequester a variety of organic substances,[7] we have evaluated two NMR methods for studying these substances in the solid state. We now demonstrate that ^{13}C NMR using the cross polarization-magic angle spinning (CP/MAS) method[8] provides a direct measure of the extent of complexation and that the deuterium quadrupolar echo method[9] gives insight concerning the motion of the guest-substrate within the annulus of the cycloamylose ring.

The ^{13}C CP/MAS spectrum of the solid complex formed by benzene with heptakis(2,6-di-*O*-methyl)-β-cyclodextrin (2,6-di-*O*-Me-β-CD) is shown in Figure 1. Measurement of the relative magnitudes of the ^{13}C resonances indicates that the complex contains 1.0 m equiv of benzene, in good agreement with the value obtained by UV measurement. A series of aromatic molecules such as monosubstituted and symmetrical disubstituted benzenes were studied; their combining ratios of "guest" to "host" are 1:1 with the exception (of ratio 1:2) for larger molecules such as biphenyl. The deuterium solid echo spectrum (Figure 2) of the equivalent complex of benzene-d_6 gave a quadrupole splitting of 48 kHz. For rigidly bound benzene, we would expect[10] a splitting of 144 kHz; rapid rotation of the benzene about its 6-fold axis within the cavity would give a splitting of 70 kHz, and about a 2-fold axis a 16-kHz splitting. Thus it is clear that rapid rotation occurs about the 6-fold axis and that the axis itself undergoes additional angular fluctuations (rms angle approximately 20°).

Combined use of both of the above methods, but particularly the latter, enables direct evaluation to be made of various factors that influence the mobility of the guest molecule within the annulus of the host. The quadrupole splittings (40.0 kHz) for $(CD_3)_2SO$ in the α-CD complex at 20 °C is substantially larger than that of the β-CD complex (7.4 kHz) at the same temperature; cooling the β-CD sample to -23 °C increases the splitting to 38.8 kHz. Both these observations reflect the decreased mobility of Me_2SO in the smaller annulus of the α-CD (4.7-5.2 Å) vs. that of the β-CD (6.0-6.4 Å). It is also possible to vary the mobility of the guest by changing the substituents attached to the host. Thus benzene-d_6 gives a splitting of 48 kHz when sequested in the 2,6-di-*O*-Me-β-CD, which increases to 68.5 kHz for the complex with 2,3,6-tri-*O*-Ac-β-CD, close to the theoretical value for pure C_6 rotation. A similar differential is found for $C_6H_5CH_2D$, the respective values being 30 and 40 kHz; the latter is close to the value (45 kHz) expected[11] for fast rotation of a methyl group about its 3-fold axis. Additional fast motion of the long molecular axis may be the source of the smaller splitting observed. Intuitively it is reasonable to expect an increase in motion due to decreased barriers to aliphatic conformational changes with increase in distance of the pendant group from the annulus; this is nicely illustrated by the decreases in the magnitude of the quadrupole splitting of $C_6H_5CH_2D$ (29 kHz) compared to $C_6H_5CH_2CH_2D$ (<5 kHz) at 20 °C. On cooling to -90 °C, the latter splitting increases to 37 kHz. This latter observation indicates that the molecular motion is almost completely confined to the methyl group, with some additional motion of the aliphatic chain being responsible for the slight reduction of the quadrupole splitting from the 44 kHz value expected for a pure methyl rotation.

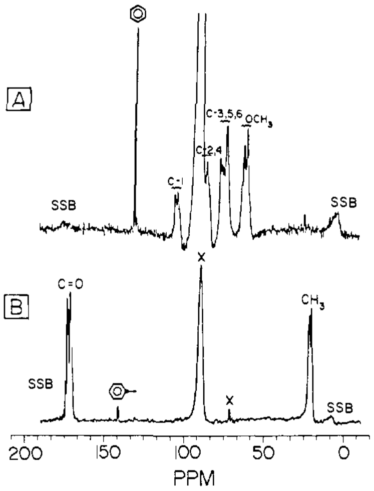

Figure 1. ^{13}C NMR of polycrystalline inclusion complexes of cycloamyloses. The experiments were performed at room temperature on a Bruker CXP-200 FT NMR spectrometer operating at 200 MHz for ^1H with an rf field of 15 G. A Delrin spinner was used, with a spinning frequency of 4.3 kHz. The spectra were plotted on the same scale. (A) Normal CP/MAS spectrum of benzene with 2,6-di-*O*-Me-β-CD. (B) Nonprotonated carbon spectrum of toluene with 2,3,6-tri-*O*-Ac-β-CD, obtained by setting a 40-μs period without proton decoupling prior to ^{13}C data acquisition (carbonyl, 172.18, 171.37, 170.36; aromatic 140.33; Delrin, 88.86; methyl, 22.12, 21.31, 20-30). Assignments are based on solution spectra, and chemical shifts are relative to external tetramethylsilane. The Delrin signals and spinning side-bands are indicated as X and SSB respectively.

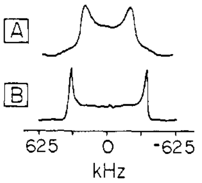

Figure 2. Deuterium NMR spectra of benzene-d_6: (A) within the cavity of 2,6-di-*O*-Me-β-CD; (B) of 2,3,6-tri-*O*-Ac-β-CD. 90° pulse length was 2.5 μs, with a τ delay of 100 μs. A recycle delay of 1.0 s was used.

Supportive evidence that is indicative of differential motion of various functional groups in the solid complexes stems from the ^{13}C CP/MAS measurements used to differentiate between the resonances of carbons that are protonated from those that are not. From the elegant concept of dipolar dephasing,[12] a delay time of ca 40-100 μs is introduced between the end of the cross-polari-

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zation period and the beginning of the ^{13}C data acquisition. The magnetization of the protonated carbons decays more rapidly than that of the tertiary carbons by relaxation with the nearby protons and decays to zero during the delay time. In this way the signals from C-1–C-6 of the host molecules are invariable eliminated. However, substantial signals are obtained for all the resonances of the guest molecule, protonated or not; furthermore, signals are also obtained from pendant substituents of the host, such as the methoxyl and acetoxyl moieties. These signals reflect the various additional degrees of freedom available to all those carbon atoms.

We conclude from this study that ^{13}C CP/MAS provides an ideal analytical tool to study not only the primary composition of complexes of the cyclodextrins. Extensions to studies of thermal, photochemical, and biological stability should be of great utility in the design of industrially useful complexes. For example we have shown that benzene-d_6 "distills" from the annulus of the 2,6-di-*O*-Me-β-CD on heating above ambient temperatures; however, when the experiment is performed in a sealed tube a thermal equilibrium exists between the guest and host.

The data obtained from the deuterium quadrupole echo experiment appear to have immense potential in studies of many other species of "guest–host" complexation, including the binding of substrates and inhibitors to solid or immobilized enzymes. The recent report by Eckman and Vega[13] of zeolite complexation of *p*-xylene is an elegant illustration of this point. These and other studies of host–guest complexes in the solid state will be discussed further.

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Synthesis and Characterization of a Novel Bis(cyclopentadienyl)titanium Hydride Complex

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We report below the synthesis and characterization of an unusual titanocene hydride complex. The complicated history of the "titanocenes" and their hydride derivatives has recently been reviewed by Toogood and Wallbridge.[1] Despite the variety of titanium hydride compounds reported, they are still a rather poorly characterized class of compounds in comparison to the hydrides of other transition metals. The only simple, terminal hydride of Ti(IV) known is the compound $(Cp^*)_2TiH_2$ (Cp^* = η^5-pentamethylcyclopentadienyl) reported by Bercaw et al.[2]

Reaction of certain organosilanes with $Cp_2Ti(CH_3)_2$ under ambient conditions, either in neat silane or in hydrocarbon solvents, leads to the remarkable and complicated reaction (1), where **2**

$$\underset{\mathbf{1}}{4Cp_2Ti(CH_3)_2} + \underset{\mathbf{2}}{8R_3SiH} \rightarrow \underset{\mathbf{3}}{2[(Cp_2TiH)_2H]} + 6R_3SiCH_3 + R_6Si_2 + 2CH_4 \quad (1)$$

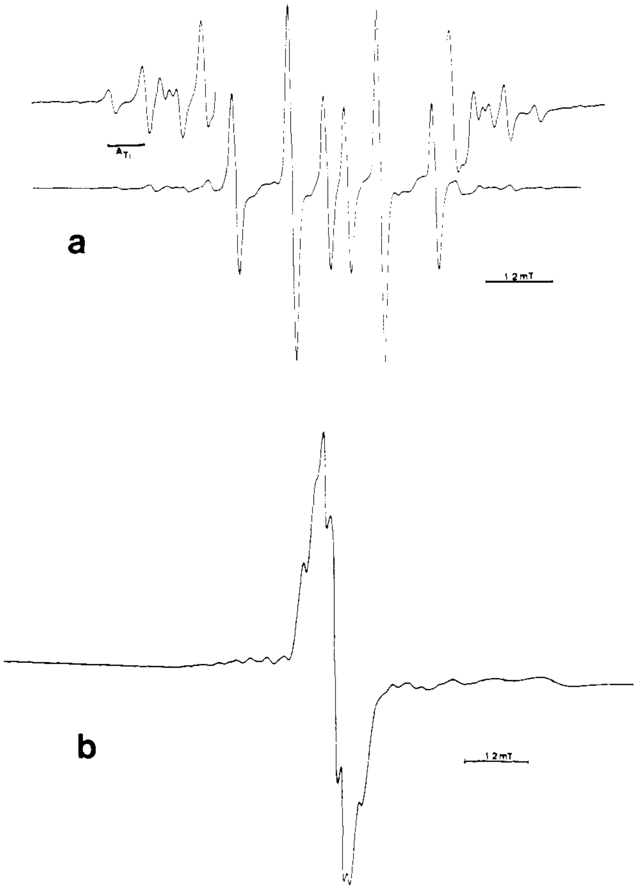

Figure 1. ESR spectra in toluene at room temperature (a) of **3** and (b) of the deuterated compound $(Cp_2TiD)_2D$.

= (e.g.) $PhSiH_3$, $(RO)_3SiH$, or $CH_3(RO)_2SiH$ but not halo-, trialkyl-, or triarylsilane.

Following admixture of the reactants in hexane under argon, the solution remains yellow for a period ranging from a few minutes to a few hours, depending on the reaction conditions. After the induction period, the onset of reaction is evident from the appearance of inky blue patches which propagate rapidly through the medium until the whole solution is intensely blue in color. The appearance of the blue color is accompanied by the evolution of a gas, which was shown by IR spectroscopy to be methane. Soon after the color change, blue-black crystals of the hydride **3** begin to deposit and after several hours, large, well-formed crystals may be recovered. In the case of $PhSiH_3$, the presence of the silicon-containing products in appropriate amounts was established by NMR spectroscopy.

The appearance of the dark blue color is also accompanied by an intense ESR signal (Figure 1a) which persists indefinitely in the absence of oxygen. This signal may also be observed in hydrocarbon solutions of freshly prepared **3**, following isolation, washing, and redissolving. These manipulations always result in some decomposition, as is evident from the appearance of a broad singlet slightly upfield of the signal due to **3**. Since the same blue compound results from the reactions of several different silanes, has an analysis corresponding closely to $C_{10}H_{10}Ti$,[3] and can also be made from dibenzyltitanocene (but not from the diphenyl analogue), the spectrum in Figure 1a is almost certainly due to the coupling of an unpaired electron on titanium to hydrogen atoms. This was confirmed by measuring the spectrum of the

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(3) Although analyses are excellent for the Cp_2Ti unit, the overall analyses have thus far not been satisfactory for the proposed formulation. Alkoxysilanes always give a small amount of contamination with alkoxytitanium(III) species, and other silanes give polysilane contaminants. Although the compound **3** is initially precipitated as well-formed crystals, we have not succeeded in recrystallizing it without decomposition. The crystal structure of **3** is presently under investigation.