

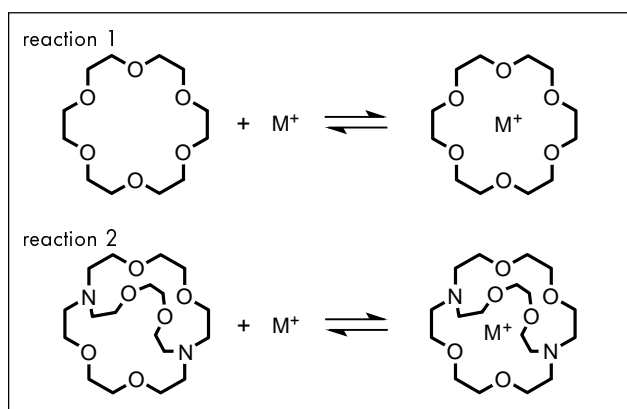
# The Complexation of the Na<sup>+</sup> by 18-Crown-6 Studied via Nuclear Magnetic Resonance

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Nuclear magnetic resonance (NMR) is arguably one of the most important analytical tools in chemistry, and undergraduate students in organic chemistry are routinely taught how to utilize <sup>1</sup>H and <sup>13</sup>C NMR for structure elucidation. NMR, however, has a vast array of uses that go far beyond simple structure analysis; consequently, many undergraduate physical chemistry laboratory courses incorporate experiments that expose the students to this technique. We have developed a student friendly experiment that teaches several important concepts of modern NMR (multinuclear capabilities, the NMR time scale, and time-averaged signals) along with some of the important concepts of thermochemical equilibria. The data, which are analyzed to yield equilibrium constants, are also in a format that teaches valuable lessons in error analysis. Further, this experiment involves safe and inexpensive compounds, such as sodium chloride, water, crown ether, and cryptand.

The 1987 Nobel Prize in chemistry went to Charles Pedersen, Donald Cram, and Jean-Marie Lehn for work that changed the focus of many chemists from covalent to non-covalent interactions (e.g., the crown ethers; ref 1). 18-Crown-6 (an 18 member ring containing 6 oxygen atoms and 12 carbon atoms) has received considerable attention as a result of its high affinity for alkali metal cations (1, 2). However, even this molecule allows alkali metal cations to pass in and out of the crown at a rate that is fast on the NMR time scale. After the discovery of cryptands, it was realized that these hosts bind alkali metal cations more tightly than do the crown ethers (2, 3). Consequently, the cryptands do not allow the cations to pass in and out of the host at a rate that is rapid on the NMR time scale. These are lessons that the students will learn empirically. A wide range of NMR techniques have been nicely described (4).



Scheme 1. Reaction between a metal ion and 18-crown-6 ether in reaction 1 and cryptand in reaction 2.

## Theory

The homogeneous cation binding constants or stability constants are nothing more than the equilibrium constants,  $K_s$ , for the reactions shown in Scheme I, where M<sup>+</sup> can be any metal cation, and the crown ether is 18-crown-6 (18C6) (reaction 1 in Scheme I). This equilibrium has been studied by a variety of experimental techniques and in a variety of solvents. The latter is very important, as  $K_s$  varies with the choice of solvent (2, 3a), and it is much larger when the crown is replaced by a cryptand (reaction 2 in Scheme I).

We study reactions 1 and 2 via NMR by tuning the instrument to detect the resonance frequency of <sup>23</sup>Na. In the presence of 18C6, there exists the possibility of two resonances: one for the uncomplexed sodium and one for the encapsulated sodium. However, if the equilibrium is fast on the NMR time scale, only one resonance will be observed. Its frequency will be the weighted average of that for the free solvated cations (Na<sub>f</sub><sup>+</sup>) and that for the encapsulation complex (c). This is the case for the Na<sup>+</sup>–18C6–water system.

The equilibrium constant for the complex formation,  $K_s$ ,

$$K_s = \frac{[c]}{[Na_f^+][18C6]} \quad (1)$$

must be evaluated using a weighted average chemical shift relationship. The observed chemical shift,  $\delta_{\text{obsd}}$ , is a concentration weighted average between the chemical shift for Na<sub>f</sub><sup>+</sup>,  $\delta_f$ , and that for the encapsulated Na<sup>+</sup>,  $\delta_c$ ,

$$\delta_{\text{obsd}} = (\delta_f x_f + \delta_c x_c) \quad (2)$$

where  $x_f$  and  $x_c$  represent the mole fractions of the free and complexed sodium ion respectively.

Note that  $\delta_{\text{obsd}} = (\delta_f + \delta_c)/2$ , the simple average, when  $[Na_f^+] = [c]$ . The chemical shift of Na<sub>f</sub><sup>+</sup> is assigned a value of 0.0 parts per million (ppm),  $x_f = [Na_f^+]/([Na_f^+] + [c])$  and  $x_c = 1 - x_f$ , hence  $(\delta_c - \delta_{\text{obsd}})$  is given by:

$$\delta_c - \delta_{\text{obsd}} = \delta_c \frac{[Na_f^+]}{[Na_f^+] + [c]} \quad (3)$$

Multiplying both sides of this expression by  $1/([Na_f^+][18C6])$ , followed by rearrangement yields,

$$\frac{\delta_{\text{obsd}}}{[18C6]} = (\delta_c - \delta_{\text{obsd}}) \frac{[c]}{[Na_f^+][18C6]} \quad (4)$$

which can be easily rearranged to:

$$\frac{\delta_{\text{obsd}}}{[18C6]} = \delta_c K_s - \delta_{\text{obsd}} K_s \quad (5)$$

Equation 5 is in the form of the Lineweaver–Burke equation (5), which can then be used to graphically determine  $K_s$  from experimental data sets of  $\delta_{\text{obsd}}$  and [18C6]. This is convenient, as eq 5 is in a  $y = mx + b$  format, and a simple plot of  $\delta_{\text{obsd}}/[18\text{C}6]$  versus  $\delta_{\text{obsd}}$  is linear. The straight line has an intercept of  $\delta_c K_s$  and a slope of  $-K_s$ .

## Experiment

Students measure the observed chemical shift for the sodium as a function of the concentration of 18C6.<sup>1</sup> The observed  $^{23}\text{Na}$  chemical shift,  $\delta_{\text{obsd}}$ , is measured relative to an internal salt–water standard that is sealed in a melting point capillary tube and placed inside the NMR tube. The chemical shift of the free  $\text{Na}^+$ , in this sealed capillary, is  $\delta_f$ . This resonance remains relatively sharp, because the  $\text{Na}^+$  cannot interact with the crown ether. It is not, however, as narrow as typical  $^1\text{H}$  and  $^{13}\text{C}$  NMR resonances, because the  $^{23}\text{Na}$  nucleus has a spin of  $3/2$ . Any nucleus with a spin greater than  $1/2$  has a quadrupole moment, which broadens NMR resonances.

The upfield resonance represents the time-averaged signal. Students will note broadening of this signal, as the concentration of 18C6 is increased. The line broadening is a result of the Heisenberg uncertainty principle ( $\Delta t \Delta E > \hbar$ ), where  $\Delta t$  is the time that the spectrometer has to measure a given spin state (called  $T_2$  or transverse relaxation time).  $T_2$

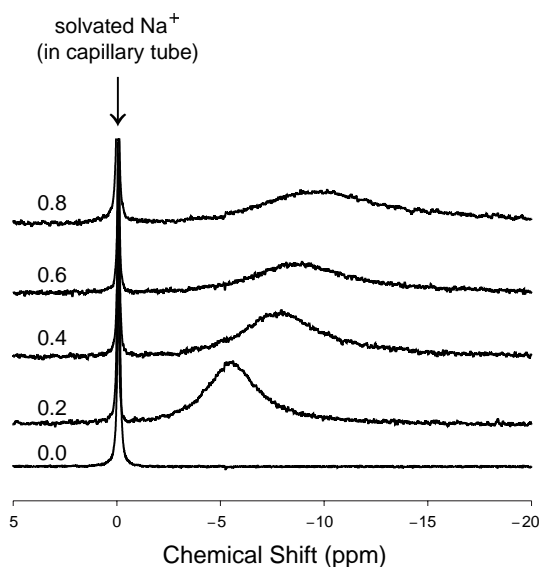


Figure 1.  $^{23}\text{Na}$  NMR spectra of samples containing 0.1 M NaCl at various concentrations of 18C6 in  $\text{D}_2\text{O}$  (to provide for a deuterium lock signal) at 298 K, recorded at 79.38 MHz on a 300 MHz  $^1\text{H}$  NMR. The resonance at 0.0 ppm represents that of the free solvated  $\text{Na}^+$  in the sealed capillary tube. Note that  $\delta_{\text{obsd}}$  decreases (shifts upfield) and broadens as [18C6] increases. 150 transients were collected with a sweep width of 20,000 Hz, a pulse width of 7.0  $\mu\text{s}$  ( $31.5^\circ$ ), an acquisition time of 0.25 s, and a delay (d1) of 1.0 s. The FIDs were processed using a line broadening factor of 1.0.

is small owing to the rapid “jumping” of the cation in and out of the complex in reaction 1. The chemical shift scale for  $^{23}\text{Na}$  is wide enough to allow precise measurement of the different signals for the chemically nonequivalent  $^{23}\text{Na}$  nuclei.

Note that in eqs 3 and 4, [18C6] represents the concentration of crown that does not contain a sodium ion, yet the total concentration of crown may be used for this variable. It can be assumed that [18C6] is virtually equal to the total 18C6 concentration, as the total concentration of 18C6 is large compared to the total concentration of sodium ions.

## Results

$^{23}\text{Na}$  NMR spectra of the  $\text{Na}^+$ –18C6– $\text{H}_2\text{O}$  system, recorded by two of our undergraduate physical chemistry students, are shown in Figure 1. Our students obtain linear relationships from plots of  $\delta_{\text{obsd}}/[18\text{C}6]$  versus  $\delta_{\text{obsd}}$  with a typical slope ( $-K_s$ ) of  $-3.63 \pm 0.24 \text{ M}^{-1}$  and an intercept ( $\delta_c K_s$ ) of  $47.3 \pm 1.8 \text{ M}^{-1}$ . The literature value for  $K_s$  is  $3.77 \text{ M}^{-1}$  (6). Note that the standard error in  $K_s$ ,  $\Delta K_s$ , is simply the error in the slope of the 95% confidence interval found from a linear regression analysis, which is described in the Supplemental Material.<sup>W</sup>

[2.2.2]Cryptand<sup>1</sup> binds the cation host more tightly than does the 18C6, and the rate of reaction 2 is slow on the NMR time scale. This allows simultaneous observation of the free

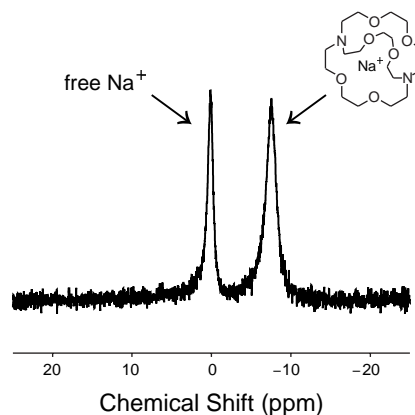


Figure 2.  $^{23}\text{Na}$  NMR spectrum of a sample containing 0.1 M NaCl and [2.2.2]cryptand in  $\text{D}_2\text{O}$  at 298 K, recorded at 79.38 MHz on a 300 MHz  $^1\text{H}$  NMR. The cryptand concentration is less than that of the  $\text{Na}^+$ , and the resonance for  $\text{Na}^+$  free and that for the encapsulated  $\text{Na}^+$  can be observed simultaneously without the use of a capillary tube standard. The resonance at 0.0 ppm represents that of the free solvated  $\text{Na}^+$ . Increasing the concentration of cryptand increases the intensity of the upfield resonance relative to that of the downfield resonance. Fifty transients were collected with a sweep width of 20,000 Hz, a pulse width of 7.0  $\mu\text{s}$ . ( $31.5^\circ$ ), an acquisition time of 0.25 s, and a delay (d1) of 1.0 s. The FIDs were processed using a line broadening factor of 1.0.

sodium cations and the encapsulated sodium cations as shown in Figure 2. There are no previously published student experiments utilizing alkali metal NMR. Increasing the concentration of cryptand increases the intensity of the upfield resonance relative to that of the downfield resonance.

### Hazards

18-Crown-6 and [2.2.2]cryptand may cause skin and eye irritation, and may be harmful if absorbed through the skin. Consequently, students should wear gloves while handling them. Deuterium oxide may be harmful if swallowed.

### Acknowledgments

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### <sup>w</sup>Supplemental Material

Instructions for the students and notes for the instructor are available in this issue of *JCE Online*.

### Note

1. 18-Crown-6 and [2.2.2]cryptand are available from Aldrich Chemicals.

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