Ultrasonic Absorption Kinetic Studies of the Complexation of Aqueous Li^+, Na^+, Rb^+, Tl^+, Ag^+, NH_4^+, and Ca^{2+} by 18-Crown-6

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Abstract: The complexation–decomplexation reaction kinetics of the macrocyclic polyether 18-crown-6 (1,4,7,10,13,16-hexaoxacyclooctadecane) with the aqueous cations Li^+, Na^+, Rb^+, Tl^+, Ag^+, NH_4^+, and Ca^{2+} have been determined from acousto-optic ultrasonic absorption data covering the 15–205-MHz frequency range, at 25 °C. These data, together with a previously reported crown ether conformational change, were analyzed in terms of a multistep mechanism that admits the possibility of water loss or conformational changes but not diffusion as being rate limiting. The complexation rate constants follow the trend $Ca^{2+} \approx Li^+ < Na^+ < K^+ \sim Cs^+ \sim Rb^+ < NH_4^+ < Tl^+ < Ag^+$.

The present strong interest in macrocyclic polyethers is attributable to their wide use in synthetic chemistry and to their suitability as models for biochemical processes. Researchers have proved the effectiveness of these macrocyclic polyethers as phase-transfer reagents,[2] catalysts in organic reactions,[3] carriers across membranes,[4] and so forth. From a synthetic standpoint, Lehn and co-workers have exploited the "dimensional" aspects of these compounds by designing and synthesizing various macrobicyclic and macrotricyclic diamines (termed cryptands) containing polyether and polythioether linkages.[5] Compared to the macrocyclic polyethers, the cryptands are more selective in their complexation of cations. In a different vein, Cram and co-workers have designed and synthesized host compounds which possess structural relationships complementary to specific guest compounds (e.g., amino acids)[6] analogous to the relationship between active sites of enzymes and their natural substrates. Cram's host compounds contain in their basic structure macrocyclic polyethers.

Most of the kinetic studies of the crown ethers have focused on solvent effects on decomplexation. For example, Shchori et al.[7] observed a consistency in the activation energy for decomplexation of several Na^+-crown complexes in various solvents. They concluded that the barrier to decomplexation is primarily the energy required to effect a conformational rearrangement of the complex. Chock[8] investigated the complexation of various monovalent cations with dibenzo-30-crown-10 in methanol. The mechanism he suggests is that of a ligand conformational change followed by a stepwise substitution of the coordinated solvent molecules by the ligand. Using this scheme, Chock evaluated the complexation rate constant and observed the reactivity pattern $K^+ < Rb^+ \sim Cs^+ \sim Tl^+$, and explained the equality in specific rates by a limitation in the diffusion-controlled rate. In the case of the cryptands, a detailed complexation mechanism is still being developed.[9]

Kinetic investigations of the host compounds prepared by Cram will certainly eventually be undertaken in an attempt to better understand enzymatic and specific complexation properties. However, prior to this undertaking the basic complexation mechanism of the simpler macrocyclic polyether compounds should be thoroughly understood.

For the above reasons a kinetic investigation of the complexation–decomplexation properties of aqueous 18-crown-6 (1,4,7,10,13,16-hexaoxacyclooctadecane) with various cations was undertaken. The polyether 18-crown-6 was studied, since it is one of those most widely used, is water soluble, and represents one of the basic structures used by Cram in his host molecules. The Ag^+ cation was also investigated, since it is known to catalyze conformational rearrangements[10] (involving bond breaking) and thus its effect on the complexation reaction rate would be of interest. The relaxation method chosen was the acousto-optic ultrasonic absorption technique, since the relaxation times of the conformational rearrangement and subsequent complexation–decomplexation reactions are within the time range accessible to this apparatus.

Experimental Section

The 18-crown-6 (Parish Chemical Company, Provo, Utah) was obtained in the form of an acetonitrile complex. The acetonitrile was removed in a vacuum desiccator maintained at 1.3 Pa for 3 days. The pure polyether melted[11] at 38–39 °C (lit. mp 39–40 °C). The inorganic salts were analytical reagent grade with the anion being chloride in all cases except for the Ag^+ and Tl^+ salts, which were nitrates. Stock solutions were all prepared by weight. Deionized, triply distilled water was used for all dilutions of stock to sample solutions.

Relaxation measurements were made on the acousto-optic ultrasonic absorption spectrometer developed in this laboratory.[12] The optical beam originates from a CW argon-ion laser operated at 514.4 nm. An output intensity of 200 mW was used, except in the case of Ag^+ where <100 mW was used to retard photoreduction of silver ions. Ultrasound absorption measurements were made at frequencies between 15 and 205 MHz at 10-MHz intervals (i.e., the odd harmonics of a 5-MHz crystal). Sample solutions were maintained at 25.0 ± 0.1 °C.

Results

The experimental ultrasonic absorption coefficients, α, were frequency normalized to the common form α/f^2. Relaxational absorption amplitudes A_i and frequencies $f_{r,i}$ were evaluated by a nonlinear least-squares fit of the data to the general equation for i relaxational processes, viz.

$$\alpha/f^2 = \sum_{i=1}^{i} \{A_i[1 + (f/f_{r,i})^2]^{-1}\} + B \qquad (1)$$

A satisfactory fit was obtained in every case where B, the background or nonrelaxational absorption, is equal to the water value, and $i = 1$. Experimental data are available in the microfilm edition or from the authors. Figure 1 shows representative plots of the single relaxations. The single relaxation parameters A and $f_{r,2}$, as well as the root mean square standard deviations, rms, are collected together in Table I. As reported previously,[13] the relaxational absorption at 101 MHz associated with the displacement of the polyether conformational equilibrium is not apparent in these spectra. This is consistent

Table I. Relaxation Parameters from Computer Analysis[a] of Equation 1

$[M^+]_0$,[b] M	[18-Crown-6]$_0$,[b] M	$f_{r,2}$, MHz	$10^{17} A$,[c] Np cm^{-1} s^2	10^{17} rms
		Lithium		
0.400	0.200	15.5	34.3	4.5
0.400	0.100	14.8	29.2	2.9
0.200	0.100	10.8	32.2	2.4
		Sodium		
0.399	0.096	17.7	340	1.4
0.299	0.096	15.2	394	0.9
0.199	0.096	12.5	486	1.6
0.199	0.048	11.7	303	3.2
		Rubidium		
0.364	0.091	22.0	83.4	1.3
0.182	0.046	14.1	98.1	2.8
0.200	0.100	12.0	223	3.3
0.100	0.050	6.54	378	2.5
		Calcium		
0.600	0.100	14.3	34.8	3.4
0.400	0.100	11.2	80.8	2.2
0.300	0.050	9.66	60.8	2.2
		Ammonium		
0.361	0.099	33.6	61.9	1.9
0.302	0.099	29.9	86.2	1.7
0.180	0.099	21.7	126	2.8
0.090	0.099	16.1	174	1.3
		Silver		
0.400	0.100	60.0	35.0	2.3
0.250	0.100	39.3	75.2	1.6
0.132	0.100	22.1	153	1.3
0.050	0.020	11.6	79.2	0.8
		Thallium		
0.346	0.099	37.7	31.6	1.2
0.244	0.099	24.5	70.0	1.8
0.122	0.050	15.5	86.4	1.4
0.100	0.099	6.52	627	4.5

[a] All symbols as defined in text. [b] Subscript zero on concentrations denotes total concentrations from diluted stock solutions. [c] Background absorption, B, fixed at 21.7×10^{-17} Np cm^{-1} s^2.

with a low free 18-crown-6 concentration in the presence of an excess of metal ions, and with a low absorption amplitude for the conformational change relative to that for the metal-polyether complexation equilibrium. Under these experimental conditions acoustic coupling between the relaxational processes is negligibly small and can be ignored in the kinetic interpretation.

Discussion

In a previous study of complexation of 18-crown-6 by K^+ and Cs^+ ions,[13] an overall two-step mechanism, analogous to that proposed by Chock[8] for the complexation of univalent ions by dibenzo-30-crown-10 in methanol, was used for the kinetic interpretation of the ultrasound absorption spectra, viz.

$$CR_1 \underset{k_{21}}{\overset{k_{12}}{\rightleftharpoons}} CR_2 \qquad (2)$$

$$M^+ + CR_2 \underset{k_{32}}{\overset{k_{23}}{\rightleftharpoons}} MCR_2^+ \qquad (3)$$

This is the simplest conceivable mechanism consistent with the data. The first step is a concentration-independent (unimolecular) conformational equilibration with $f_{r,1} = 101$ MHz, such that $(k_{12} + k_{21}) = 6.3 \times 10^8$ s^{-1}, see eq 4, and is fast relative to the second step where the metal ion enters the cavity of the CR_2 conformer of the cyclic ether.

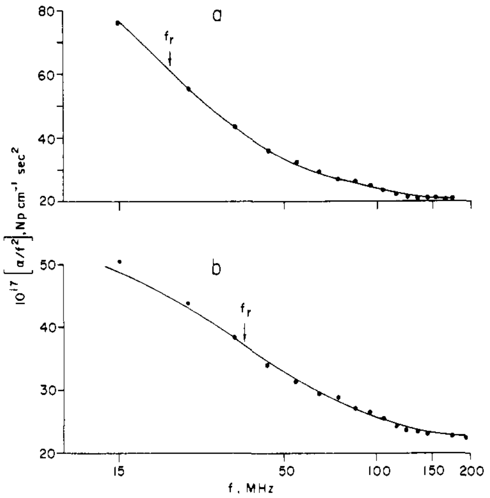

Figure 1. Plot of α/f^2 vs. f (dots are experimental point, line is best fit curve) for (a) 0.364 M RbCl and 0.091 M 18-crown-6; (b) 0.346 M $TlNO_3$ and 0.099 M 18-crown-6.

Table II. Equilibrium and Rate Constants for Complexation–Decomposition[a] at 25 °C

M^+	k_{23}', M^{-1} s^{-1}	k_{32}, s^{-1}	K_T[c]
Li^+	$\sim 8 \times 10^7$	$\sim 6 \times 10^7$	~1.3
Na^+	2.2×10^8	3.4×10^7	6.3
K^+[b]	4.3×10^8	3.7×10^6	115.0
Rb^+	4.4×10^8	1.2×10^7	36.3
Cs^+[b]	4.3×10^8	4.4×10^7	9.8
Ca^{2+}	$< 1.0 \times 10^8$	$> 3.2 \times 10^7$	<3.2
NH_4^+	5.6×10^8	4.4×10^7	12.6
Ag^+	11.2×10^8	3.5×10^7	31.6
Tl^+	9.0×10^8	4.8×10^6	186.0

[a] All symbols as defined in text. [b] Data taken from ref 13. [c] Data taken from ref 14 and 15.

In the absence of close acoustic coupling between the relaxations, the rate constants for the two steps are related to the corresponding relaxation times by the simple equations:

$$\tau_1^{-1} = 2\pi f_{r,1} = k_{12} + k_{21} \qquad (4)$$

and

$$\tau_2^{-1} = 2\pi f_{r,2} = k_{23}'\{\overline{CR}_1 + \overline{CR}_2 + \overline{M}^+ + K_T^{-1}\} \qquad (5)$$

where the subscripts 1 and 2 refer to eq 2 and 3, K_T is the overall formation constant for the metal-crown ether complex, the bars refer to equilibrium concentrations, and the further equalities hold that

$$k_{23}' = k_{23}/(1 + K_{21}) \qquad (6)$$

$$K_T^{-1} = k_{32}/k_{23}' \qquad (7)$$

and $K_{21} = k_{21}/k_{12}$. Arguments have been presented[13] confirming that the complexation rate is not diffusion controlled.

A knowledge of K_T for the various metal complexes[14] and the ammonium complex[15] allows us to calculate the corresponding k_{23}' and k_{32} values from eq 5 and 7 (Table II). Representative plots of eq 5 are shown in Figures 2 and 3. The three rate constants (k_{23}, k_{12}, and k_{21}) can only be determined if K_{21} is known. In the previous study[13] an estimated upper limit for K_{21} of 22.5 was obtained when it was assumed that k_{23} might be equal to the diffusion-controlled rate constant $k_D = 1.0 \times 10^{10}$ M^{-1} s^{-1}. Discussion of the complexation rate was

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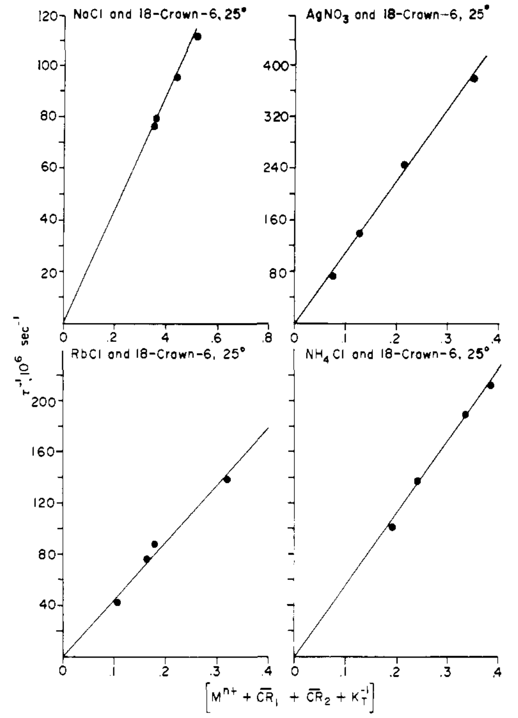

Figure 2. Plot of the reciprocal relaxation time $\tau^{-1} = 2\pi f_r$ vs. $[\overline{\mathrm{M}^{n+}} + \overline{\mathrm{CR}_1} + K_\mathrm{T}^{-1}]$ for Na^+, Ag^+, Rb^+, and $\mathrm{NH_4}^+$ complexing 18-crown-6 at 25 °C. The straight line is a linear least-squares fit of the experimental data points. The diameter of the points corresponds to the precision of the data.

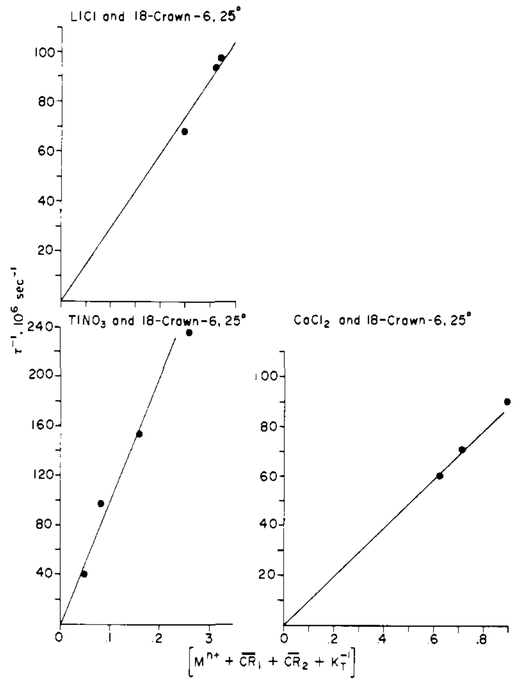

Figure 3. Plot of the reciprocal relaxation time $\tau^{-1} = 2\pi f_r$ vs. $[\overline{\mathrm{M}^{n+}} + \overline{\mathrm{CR}_1} + \mathrm{CR}_2 + K_1^{-1}]$ for Li^+, Tl^+, and Ca^{2+} complexing 18-crown-6 at 25 °C. The straight line is a linear least squares with the diameter of the points corresponding to the precision of the data.

restricted to comments on the experimentally observed k_{23}' and k_{23}. However, since K_{21} is constant for all ions, variations in k_{23}' and k_{23} are identical. In this instance we see that Ag^+ and Tl^+ complex with the polyether much more rapidly than do the ions with inert gas electronic configurations.

Currently a temperature dependence study of the system is in progress. Using a method described in detail by Farber and Petrucci,[16] based on the simultaneous analysis of the temperature dependence of τ_1 and the absorption amplitude A, a value of 1.6×10^{-2} has been obtained for K_{21}. Full details will be published at a later date. The result, however, is pertinent to the present discussion in that it shows, from eq 6, that $k_{23}' \simeq k_{23}$. The rate constants for eq 2 are therefore $k_{12} = 6.3 \times 10^8\ \mathrm{s}^{-1}$ and $k_{21} = 1 \times 10^7\ \mathrm{s}^{-1}$. We can now proceed with an analysis of the details of the complexation step, eq 3.

Diffusion control can be immediately dismissed because k_{23} is almost two orders of magnitude smaller than k_D. It would also be difficult to rationalize the much larger k_{23} values for Ag^+ and Tl^+ using diffusion arguments.

The possible multiplicity of the complexation step concerns us here. Metal complexation reactions are commonly described as occurring in a number of steps which involve intermediate, solvent-separated, ion pairs in dynamic equilibrium with the final complex.[17] Typically the rate-determining step in ligand substitution of an aquo ion is the rate of loss of primary coordinated water from the ion. The rate constant for this step, k_ex, is both characteristic of the ion and virtually independent of the ligand. The slow step may be preceded by a fast outer-sphere equilibration step with an equilibrium constant K_os such that the experimentally observed rate constant k_obsd is equal to $K_\mathrm{os}k_\mathrm{ex}$. Specific solvent exchange rate constants, k_ex, are known[18] for the 1A metal ions and Ca^{2+}. Noticeably they are all an order of magnitude greater than the k_{23} values obtained here, but the variations in k_{23} and k_ex with the ions are almost parallel, differing only between Rb^+ and Cs^+. No values of k_ex are known for $\mathrm{NH_4}^+$, Ag^+, and Tl^+. As was pointed out above the two-step mechanism is the simplest one which is consistent with the data. This lack of correspondence between k_{23} and k_ex would suggest that eq 3 actually consists of a number of steps.

The first alternative multistep mechanism to consider is that eq 3 is preceded by an acoustically undetectable fast preequilibration step with an equilibrium constant K_os. In this situation $k_{23} = K_\mathrm{os}k_\mathrm{ex}$. This model is quite typical of the Eigen mechanism. K_os is difficult to evaluate theoretically, since the crown ether is not spherically symmetrical. Nevertheless K_os, when calculated for a spherical uncharged ligand at a distance of closest approach to the cation of 5 Å using the Fuoss equation,[19] is equal to 0.32. Presumably $K_\mathrm{os} < 1$ for unsymmetrical ligands also, in which case a solvent exchange rate-controlling step is consistent with the observed rate constants.

It is conceivable that binding the ligand to the ion will require the loss of more than one primary coordinated water molecule even to the point of complete desolvation. That this should happen in one step (eq 3) is unlikely on energetic grounds,[18] i.e., the activation energy for a single desolvation step would be very large and inconsistent with the rapid rate of complexation. The process is more likely to occur in a number of steps analogous to the complexation of a metal ion by a multidentate ligand (e.g., EDTA). Specific rate constants for complexation of multidentate ligands by 1A and 2A ions are known[18,20] to be lower than k_ex. Analogous reactions on transition metal ions, however, are frequently faster than the rate of first substitution.[18] These observations could account for the differences we have observed between the 1A ions and Ca^{2+}, and Ag^+ and Tl^+. Concurrent with this idea, substitution into Ag^+ and Tl^+ could be faster because fewer primary solvated water molecules need to be lost.

A third modification to consider is the kinetics of complexation may not be ligand independent. For example, whereas the k_{23} values level off at $4.3 \times 10^8\ \mathrm{M}^{-1}\ \mathrm{s}^{-1}$ for K^+, Rb^+, and Cs^+ with the crown polyether, the complexation rates follow the definite sequence $\mathrm{K}^+ < \mathrm{Rb}^+ < \mathrm{Cs}^+$ with EDTA and NTA as ligands.[20] Since the ion solvations should be the same in the presence of both ligands desolvation processes should be similar. Part of the reason for the change in trends may be that the polyether undergoes a second conformational change. There is no kinetic evidence for this, but a third conformer for the metal bound ligand has been reported from x-ray studies.[21] In the case of the polarizable cations Ag^+ and Tl^+ there is the distinct possibility that the removal of primary solvated water other than the first molecule is ligand assisted perhaps through a covalently bonded interaction on first substitution. This effect is analogous to the directional trans effect in substitutions of square-planar complexes.

The kinetic evidence appears to suggest a mechanism more complex than the elementary two-step mechanism used in data interpretation. Presently we cannot distinguish our preference for any one of the proposed modifications. Indeed all might contribute to different degrees. Further insight may be gained from temperature dependent studies and investigations using other crown polyethers. Both studies are in progress.

It is apparent from the variations in k_{23} that the overall stability constants K_T are not solely determined by the changes in the rates of decomplexation. The specificity that the ligand has for a particular metal is for the most part determined by the decomplexation rate, yet release of the ligand on demand is still a very rapid process, and is of great significance to mass transport processes. 18-Crown-6 appears to be a rather flexible molecule capable of rapid conformational changes in both its complexed and uncomplexed state, which makes it suitable as a building block for a catalyst.

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Supplementary Material Available: listing of the α/f^2 data for the various cations complexed by 18-crown-6 (14 pages). Ordering information is given on any current masthead page.

References and Notes

(1) (a) University of Utah; (b) University of Santiago, Spain; (c) Oklahoma State University.
(2) G. W. Goekel and H. D. Durst, *Aldrichimica Acta*, **9**, 3 (1976).
(3) G. W. Goekel and H. D. Durst, *Synthesis*, submitted for publication.
(4) K. H. Wong, K. Yagi, and J. Smid, *J. Membr. Biol.*, **18**, 379 (1974).
(5) B. Dietrich, J.-M. Lehn, and J. P. Sauvage, *Tetrahedron Lett.*, **34**, 2885 (1969).
(6) D. J. Cram, *Pure Appl. Chem.*, **43**, 327 (1976).
(7) E. Shchori, J. Jagur-Grodzinski, and M. Shporer, *J. Am. Chem. Soc.*, **95**, 2842 (1973).
(8) P. B. Chock, *Proc. Natl. Acad. Sci. U.S.A.*, **69**, 1939 (1972).
(9) V. M. Loyola, R. G. Wilkins, and R. Pizer, *J. Am. Chem. Soc.*, **97**, 7382 (1975).
(10) L. Casser, P. E. Eaton, and J. Halpern, *J. Am. Chem. Soc.*, **92**, 3515, 6366 (1970).
(11) R. N. Greene, *Tetrahedron Lett.*, 1793 (1972).
(12) M. M. Farrow, S. Olsen, N. Purdie, and E. M. Eyring, *Rev. Sci. Instrum.*, **47**, 657 (1976).
(13) G. W. Liesegang, M. M. Farrow, N. Purdie, and E. M. Eyring, *J. Am. Chem. Soc.*, **98**, 6905 (1976).
(14) R. M. Izatt, R. E. Terry, B. L. Haymore, L. D. Hansen, N. K. Dalley, A. G. Avondet, and J. J. Christensen, *J. Am. Chem. Soc.*, **98**, 7620 (1976).
(15) H. K. Frensdorff, *J. Am. Chem. Soc.*, **93**, 600 (1971).
(16) H. Farber and S. Petrucci, *J. Phys. Chem.*, **80**, 327 (1976).
(17) H. Diebler and M. Eigen, *Z. Phys. Chem.* (*Frankfurt am Main*), **20**, 229 (1959).
(18) H. Diebler, M. Eigen, G. Ilgenfritz, G. Maass, and R. Winkler, *Pure Appl. Chem.*, **20**, 93 (1969).
(19) R. M. Fuoss, *J. Am. Chem. Soc.*, **80**, 5059 (1958).
(20) M. Eigen and G. Maass, *Z. Phys. Chem., N.F.*, **49**, 163 (1966).
(21) M. A. Bush and M. R. Truter, *Chem. Commun.*, 1439 (1970).

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^{15}N and ^{17}O Nuclear Magnetic Resonance of Organophosphorus Compounds. Experimental and Theoretical Determinations of $^{15}N-^{31}P$ and $^{17}O-^{31}P$ Nuclear Spin Coupling Constants

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Abstract: Natural abundance ^{15}N and ^{17}O NMR studies have been carried out on a series of organophosphorus compounds for the purpose of determining $^{31}P-^{15}N$ and $^{31}P-^{17}O$ nuclear spin couplings. The $^{31}P-^{15}N$ couplings are sensitive to both electronegativity of substituent and conformation. Finite perturbation coupling calculations within the CNDO/2 approximation were performed to probe the effect of conformation and structure as well as the trigonal-pyramidal geometry balance at the nitrogen. Theoretical $^{31}P-^{17}O$ couplings were also computed for a wide variety of P-O bonding situations, giving clear evidence for the dominance of the coupling by the Fermi contact mechanism. New experimental $^{31}P-^{17}O$ couplings include those for $R_3P{=}O$ for R = C, N, F, Cl, and Br.

Pulsed Fourier transform NMR techniques have made the observation of a "weak" nucleus such as ^{13}C routine. While natural abundance ^{15}N and ^{17}O NMR spectra are also possible using the same techniques, their lower natural abundance, long T_1's (for ^{15}N), and quadrupolar broadening associated with ^{17}O resonance have slowed progress in their use. Our previous studies of organophosphorus compounds have relied on ^{13}C NMR[2] and more recently ^{15}N NMR[3] with the goal of a better understanding of the nature of chemical bonding involving phosphorus. Of special concern is the sensitivity of nuclear spin couplings to changes in the electronic structure of organophosphorus compounds as governed by geometrical deformations and electronegativity effects. Our previous work[3] on $^1J_{P-N}$ and that of others[4-8] have concentrated on the signs and magnitudes of this coupling as a function of the oxidation state at phosphorus. There has been some prior study of $^{31}P-^{17}O$ couplings.[9] A very early report[9a] encountered difficulties in peak assignment, which led to an uncertainty with values reported therein. The present work is directed toward an exploration of electronegativity effects of the magnitudes of these