theory to predict the activation energy of a particular reaction and hence assign a probable mechanism on the basis of these calculations. The results show that the reactions of complexes with a certain primary metal atom may not proceed always by the same mechanistic path. Moreover, the model does not definitely assign the probably geometry of the intermediate in cases where it predicts one type of mechanism. Crude as it now stands, we believe that as more data are accumulated on the precise measurement of the activation energies of a large number of reactions (and on the electronic spectra of the complexes) further refinements of this model will be able to correlate the data and, perhaps, predict the activation energy of a reaction yet to be carried out.

More recent experimental evidence and speculation about the mechanisms of substitution reactions for Cr(III) and Co(III) reactions does not arrive at a consensus. Taking into account both entropies and enthalpies of activation for a number of Co(III) reactions, Tobe concludes that they are all essentially dissociative reactions with the probable intermediate being a trigonal bypyramid if the entropy is positive and a tetragonal pyramid if not.[22] However, the energy difference between these two is small so that a very small difference in the ligand, for example, can change the intermediate. Duffy and Earley[23] conclude that the anation of $Cr(NH_3)_5OH_2^{3+}$ proceeds *via* an SN1IP reaction, whereas on the basis of an nmr study of the aquation of $Co(CH_3NH_2)_5Cl^{2+}$ Parris[24] concludes that an SN1 mechanism is involved and suggests that the analogous Cr(III) complex probably proceeds *via* an SN2-type mechanism.

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Chelation of Uranyl Ions by Adenine Nucleotides. II. Proton Magnetic Resonance Investigation of the Uranyl Nitrate–Adenosine 5′-Monophosphate Chelate in D_2O at Basic pD[1]

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Abstract: Proton magnetic resonance spectra (100 MHz) of various mixtures of uranyl nitrate and adenosine 5′-monophosphate in D_2O at pD ~10 have been obtained and analyzed. In 0.1 *M* equimolar solution all 5′-AMP proton resonances experience a downfield shift, specifically, H_8 (0.46 ppm), H_2 (0.31 ppm), $H_{1'}$ (0.03 ppm), $H_{2'}$ (2.87 ppm), $H_{3'}$ (0.74 ppm), $H_{4'}$ (2.35 ppm), $H_{5'}$ (1.04 ppm), and $H_{5''}$ (0.32 ppm). The uranium-induced purine proton shifts are attributed to destacking of the adenine rings plus complete elimination of the specific phosphate deshielding of H_8. The movement of the ribose proton signals is believed to result from the formation of a dinuclear sandwich-type chelate in which one uranyl group is chelated by the 2′- and 3′-ribose oxygen atoms of one 5′-AMP molecule and by a phosphate oxygen and the 3′-oxygen of a second AMP molecule, and a second uranyl group is chelated by the 2′- and 3′-oxygens of the second AMP molecule and a phosphate oxygen and the 3′-oxygen of the first AMP. This chelate structure is so strong that the free ligand resonances and the complexed ligand resonances appear simultaneously in the spectrum of a mixture containing excess AMP, with no difference in their purine proton peak widths being detectable. The compatibility of the proposed structure and its pmr spectrum is discussed.

This paper is a continuation of the investigation of the reaction of UO_2^{2+} with nucleotides. In the previous paper[4] we interpreted pH titrations of mixtures of adenine nucleotides and $UO_2(NO_3)_2$. For the present paper we have carried out a proton magnetic resonance investigation of the uranyl nitrate–adenosine 5′-monophosphate 1:1 chelate (U-AMP) in D_2O. Gelation and precipitation limited this pmr study to basic pD.

Experimental Section

Materials. All nucleotides were Sigma Chemical Co. Sigma grade used as received without further purification. They were standardized by titration. D_2O (99.82%) was purchased from Volk Radiochemical Co. Eastman grade aqueous 10% tetramethylammonium hydroxide was purchased from Distillation Products Industries. Fisher Certified Reagent grade uranyl nitrate hexahydrate was used.

Preparation of Solutions. Each aqueous nucleotide solution was first made up to ~0.05 *M* by direct weighing of the desired amount and then raising the pH with 10% $(CH_3)_4NOH$ to the desired value. The aqueous solution was then lyophilized overnight, and the residue

(1) (a) This paper is based on work performed under contract with the U. S. Atomic Energy Commission at the University of Rochester Atomic Energy Project and has been assigned Report No. UR-49-948; (b) presented in part at the Second International Symposium on Nuclear Magnetic Resonance, Sao Paolo, Brazil, July 1968.
(2) On leave from University of Roorkee, Roorkee, India
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(4) I. Feldman, J. Jones, and R. Cross, *J. Am. Chem. Soc.*, **89**, 49 (1967).

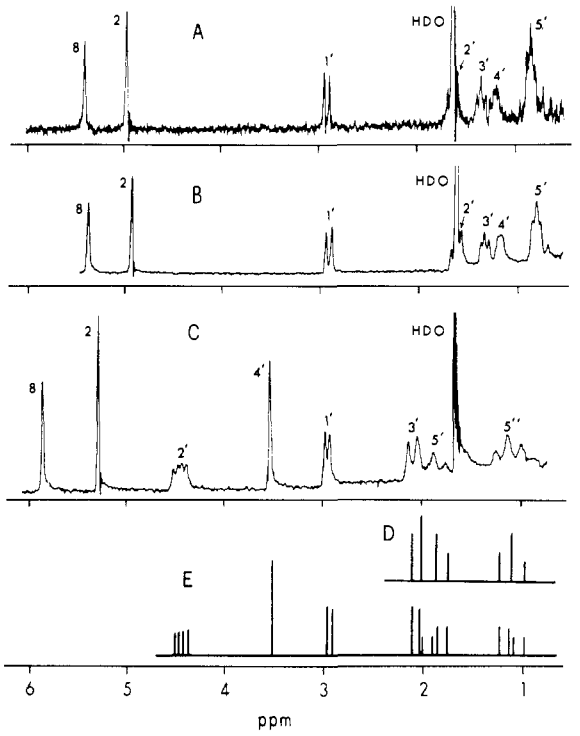


Figure 1. 100-MHz pmr spectra of 5′-AMP and uranyl nitrate–5′-AMP mixtures in D_2O at pD ~ 10 and 27°. Chemical shifts measured downfield from methyl resonance frequency of tetramethylammonium ion. Numbers on figures correspond to the AMP proton assignments (see text): (A) 0.1 *M* 5′-AMP, no uranium added, original spectrum; (B) 0.1 *M* 5′-AMP, no uranium added, spectrum accumulated 16 times; (C) 0.1 *M* 1:1 uranyl nitrate–5′-AMP mixture (U-AMP), spectrum accumulated 16 times and printed at twice the normal gain; (D) 3′,5′, and 5″ resonances of 0.1 *M* U-AMP spectrum computed with LAOCOON II program using 5.0-cps peak widths; (E) ribose part of 0.1 *M* U-AMP spectrum computed with 1.0-cps peak widths.

was redissolved in D_2O to the desired final concentration. This process of lyophilization and redissolution in D_2O was repeated twice to minimize the HDO spectral peak.

Mixtures of uranyl nitrate and nucleotide were prepared as follows. A freshly prepared aqueous solution of nucleotide in the divalent form (*i.e.*, after addition of 2 moles of $(CH_3)_4NOH$ per mole of nucleotide) was first added to a uranyl nitrate solution to give the desired molar ratio of uranium to nucleotide. A yellowish white precipitate was always obtained.[5] To this mixture was then added $(CH_3)_4NOH$ dropwise with stirring until the precipitate dissolved, and this addition was continued until the desired pH was attained. About 4 moles of base per mole of 5′-AMP in a 1:1 mixture gave pH ~9.5. This solution was then alternately lyophilized and redissolved three times in D_2O. The recorded pD value is the final pH meter reading plus 0.4.[6]

Pmr Spectra. All spectra were recorded with a Jeolco 4H-100 (100 MHz) nmr spectrometer kept in a 24° constant-temperature room. The probe temperature was 27°. Chemical shifts were measured relative to the methyl group resonance frequency of the $(CH_3)_4N^+$ ion as internal standard, since each solution contained $(CH_3)_4N^+$ as a result of pH adjustment with $(CH_3)_4NOH$. Previous work[7] showed that $(CH_3)_4N^+$ does not affect the nucleotide pmr spectra significantly.

A Jeolco JRA-1 spectrum accumulator was used to increase the signal-to-noise ratio when necessary.

Results and Discussion

Identification of Resonances in U-AMP Pmr Spectrum. In Figure 1 are presented 100-MHz pmr spectra of 5′-AMP and mixtures of uranyl nitrate and 5′-AMP in D_2O at various molar ratios. The pD was 10.2 ± 0.2 in all cases.

The assignments of the $H_{2'}$, $H_{3'}$, and $H_{4'}$ resonances in the 5′-AMP spectrum (Figures 1A, 1B, 2A) were made in an earlier paper.[7] The remaining 5′-AMP proton signals had been previously identified by Jardetzky and Jardetsky.[8]

The most significant difference between the 5′-AMP spectrum and the spectrum (Figure 1C) of a 1:1 0.1 *M* mixture of uranyl nitrate and 5′-AMP at pD 10 is the presence of the quadruplet at 4.44 ppm and the singlet at 3.52 ppm in the latter spectrum. Since the two singlets at the extreme left side of Figure 1C obviously are the purine H_8 and H_2 peaks, the new quartet and singlet must represent ribose protons whose resonances were shifted downfield *at least* 2.87 and 1.95 ppm, respectively (*i.e.*, as measured from the most downfield ribose proton peak, ~1.57 ppm, in Figure 1B). Two other ribose proton resonances were shifted significantly downfield by uranium as indicated by the four new peaks between 1.75 and 2.15 ppm. The $H_{1'}$ is almost unaffected by uranium. The remaining ribose proton band is the apparent triplet near 1.13 ppm. In the normal spectrum this triplet is obscured by the spinning noise of the reference signal, but spectrum accumulation (16×) revealed its presence.

We have identified the ribose proton signals as shown in Figure 1C on the following basis. The doublet at 2.94 ppm is undoubtedly the $H_{1'}$ resonance, being only 0.03 ppm downfield from the $H_{1'}$ location in Figure 1A, *i.e.*, in absence of uranium. Irradiation of the quadruplet at 4.44 ppm collapsed the $H_{1'}$ resonance to a singlet. Hence, this quadruplet must be $H_{2'}$. (This $H_{2'}$ irradiation did not also identify $H_{3'}$ because, as discussed below, there is partial overlap between an $H_{3'}$ doublet and an $H_{5'}$ triplet which obscures the effect of $H_{2'}$ irradiation.) First-order analysis of the $H_{2'}$ quadruplet gives coupling constant $J_{1'-2'}$ = 5.0 and $J_{2'-3'}$ = 8.0 cps. To the left of the water peak in Figure 1C there appear to be two doublets, the separation of the left one being 9.5 cps and of the other being 11 cps. We believe that the relatively high intensity of the right peak of the left doublet (*i.e.*, the third peak to the left of HDO) results from a superposition (see Figures 1D and 1E) of a doublet at 2.06 ppm having J = 8.0 cps, and therefore representing $H_{3'}$, and a quadruplet at 1.85 ppm. This latter multiplet, like the pseudo-triplet at 1.13 ppm, has coupling constants 15 and 10 cps, but its component peaks have widths of about 6 cps. This would indicate that the 1.85 and 1.13 ppm signals represent $H_{5'}$ and $H_{5''}$, −15 cps being their geminal coupling constant and +10 cps being the coupling of each to phosphorus. By elimination, the singlet at 3.52 ppm must then be $H_{4'}$. We can offer no explanation why $H_{4'}$, or any other ribose proton resonance, should be a singlet, but it is a fact.

These coupling constants and chemical shifts for the U-AMP spectrum were obtained with an IBM 360-44 computer using the LAOCOON II program.[9] The computed ribose portion of the U-AMP spectrum using peak widths of 1.0 cps is presented as Figure 1E. To

(5) The conditions under which precipitates form and redissolve in mixtures of uranyl nitrate and nucleotide are discussed in the first paper[4] of this series.

(6) P. K. Glasoe and F. A. Long, *J. Phys. Chem.*, **64**, 188 (1960).

(7) I. Feldman and R. P. Agarwal, *J. Am. Chem. Soc.*, in press.

(8) C. D. Jardetzky and O. Jardetzky, *ibid.*, **82**, 222 (1960).

(9) S. Castellano and A. A. Bothner-By, *J. Chem. Phys.*, **41**, 3863 (1964).

show the superposition of the $H_{3'}$ doublet and the $H_{5'}$ quadruplet when a larger peak width is considered, the portion of the spectrum containing the $H_{3'}$, $H_{5'}$, and $H_{5''}$ signals was computed using 5-cps peak widths and is presented as Figure 1D.

Indirect Effect of Uranyl Complexation on Adenine Proton Resonances. The downfield movements of H_8 and H_2 caused by addition of an equimolar amount of uranium to 0.1 *M* 5′-AMP are 0.46 and 0.31 ppm, respectively. The latter value is a little larger than the effect of destacking[10] on the H_2 resonance, 0.14 ppm, which Schweizer, *et al.*,[13] found by extrapolation of the H_2 chemical shifts of 5′-AMP from 0.1 *M* to infinite dilution. In our opinion this difference is probably due to the uncertainty of their extrapolated value since they studied solutions no lower in concentration than 0.05 *M*.

Some evidence for our view is the fact that for a 5′-AMP concentration change from 0.2 to 0.1 *M* at pD 10 there is no change in either the H_2 or H_8 resonance when uranium is present in equimolar amounts, but in absence of uranium there is a downfield shift of 0.08 ppm for H_2 and 0.02 ppm for H_8. The uranium-induced H_8 movement, however, is too large to be attributed to destacking, since H_8 is affected even less by destacking than is H_2. Most of the difference between the uranium-induced H_8 shift and the destacking effect to be expected, 0.10 ppm, for H_8 is undoubtedly due to the fact that the extrapolation experiment of Schweizer, *et al.*, involved only small change in the specific deshielding[14] of H_8 by the phosphate group, whereas this effect should be completely eliminated by the binding of uranium to phosphate. In addition, the H_8 and H_2 changes are an order of magnitude lower than the uranium-produced shifts in the resonances of the two ribose protons represented by the new quartet and singlet.

It seems evident, therefore, that the uranium-produced downfield movements of H_8 and H_2 do *not* imply that uranium is bound to the adenine group in the U-AMP complex at basic pD.

Stoichiometry of U-AMP Chelate. The pmr spectra show that only a 1:1 complex exists in a 0.1 *M* equimolar U-AMP mixture and in U-AMP mixtures containing excess nucleotide. In Figure 2 are shown the pmr spectra of 1:1, 1:2, and 1:3 uranyl nitrate:5′-AMP mixtures at pD 10, each containing 0.2 *M* 5′-AMP. It is obvious that in each case the spectrum is simply a superposition of the same U-AMP spectrum and the spectrum of uncomplexed 5′-AMP with the relative intensities of their respective resonances being indicative of the ratio of the two forms of the ligand molecule. This ratio is approximately unity in the 1:2 mixture and one-half in the 1:3 mixture, showing that the U-AMP stoichiometry is 1:1 in each case. There is a small contribution of the free ligand spectrum in the spectrum of the 0.2 *M* equimolar mixture, despite the fact that 0.1 *M* equimolar mixture (Figure 1C) showed no spectrally detectable free ligand content even after the noise was removed by spectrum accumulation. The small amount of free ligand in 0.2 *M* solution was not detected each time we did the experiment. It may be due to the experimental difficulty of attaining equilibrium, *i.e.*, of completely solubilizing all the previously precipitated uranium as the 1:1 complex before formation of some complex containing two uranium atoms per nucleotide. The existence of this latter complex is shown by the fact that the spectrum of a 0.1 *M* equimolar mixture was indistinguishable from the spectrum of a mixture containing twofold excess uranyl nitrate (*i.e.*, 0.1 *M* 5′-AMP, 0.2 *M* U). The presence of some free ligand in the 0.2 *M* equimolar solution, but not in the equimolar 0.1 *M* solution, verifies the presence of a little of the higher complex in the former solution and its absence in the latter solution.

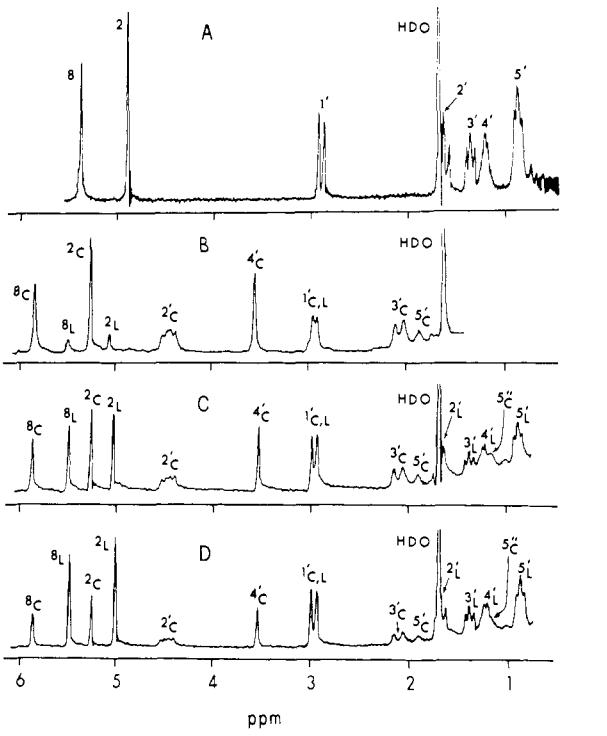


Figure 2. 100-MHz pmr spectra of 5′-AMP and uranyl nitrate–5′-AMP mixtures in D_2O at pD ~10 and 27°. Chemical shifts measured downfield from methyl resonance of tetramethylammonium ion. Numbers on figures correspond to the AMP proton assignments (see text). Subscripts L and C refer to free ligand and complexed ligand resonances, respectively: (A) 0.2 *M* 5′-AMP, no uranium added, original spectrum; (B–D) 16 times accumulated spectra of uranyl nitrate–5′AMP mixtures *each* containing 0.2 *M* 5′-AMP but different U:AMP molar ratios. U:AMP molar ratios are 1:1 for B, 1:2 for C, and 1:3 for D.

The simultaneous presence of the resonance signals of the protons of both the complex and the free ligand when excess ligand is present shows that the U-AMP complex, once formed, is very strong. The ligand exchange rate is so slow that the widths of both purine peaks were, within experimental error, unchanged by addition of uranium.

Structure of U-AMP Chelate. It will be evident from the following discussion that uranium in the complex is actually bound to the phosphate group and to the ribose 2′- and 3′-oxygen atoms.[15]

(10) Evidence is ample[11-13] to show that in aqueous solution, or in D_2O, nucleotides tend to self-associate by vertical stacking of the adenine rings to a degree dependent on concentration. Destacking of the six-membered purine ring is indicated by a downfield shift of the H_2 resonance.[11,13] The change in H_8 is the net effect of destacking and specific deshielding by phosphate.[15]

(11) A. D. Brown, M. P. Schweizer, and P. O. P. Ts'o, *J. Am. Chem. Soc.*, **89**, 3612 (1967).

(12) G. P. Rossetti and K. R. van Holde, *Biochem. Biophys. Res. Commun.*, **26**, 717 (1967).

(13) M. P. Schweizer, A. D. Broom, and P. O. P. Ts'o, *J. Am. Chem. Soc.*, **90**, 1042 (1968).

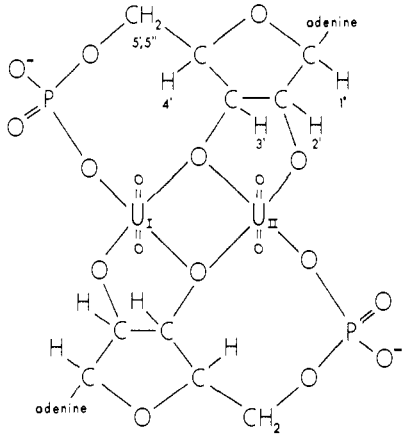
(14) This specific deshielding of H_8 by the phosphate in 5′-AMP is believed[13] to be due to electrostatic attraction of the phosphate group for H_8, resulting in polarization of the C_8–H_8 bond.

Table I. Estimated Contributions of Magnetic Anisotropy of Uranyl Group to Uranium-Induced Chemical Shifts of U-AMP Ribose Protons

Proton	R_I, Å	θ_I, deg	R_{II}, Å	θ_{II}, deg	$\sigma_{m,I}$, ppm	$\sigma_{m,II}$, ppm	$\sigma_{m,I} + \sigma_{m,II}$, ppm	σ^*_{expt}, ppm	Δ, ppm
1′	3.6	55	6.0	60	−0.02	−0.10	−0.12	0.03	0.15
2′	3.6	100	6.0	95	−1.79	−0.41	−2.20	2.87	5.07
3′	3.8	105	4.4	100	−1.33	−0.97	−2.30	0.74	3.04
4′	3.7	40	3.4	50	+1.37	+0.56	+1.93	2.35	0.42
5′	6.5	60	6.0	60	−0.08	−0.10	−0.18	1.04	1.22
5″	6.5	85	5.5	80	−0.32	−0.50	−0.82	0.32	1.14

Neither 2′-AMP nor 3′-AMP solubilizes uranyl ion in equimolar mixture. Mixtures containing 0.1 *M* uranyl nitrate and 0.2 *M* nucleotide are viscous, but they seem to be stable solutions. The 1:2 U:3′-AMP spectrum showed only the HDO peak. The 1:2 U:2′-AMP spectrum was indistinguishable from a 2′-AMP spectrum except for a greatly decreased signal-to-noise ratio. It seems evident that in both mixtures the noticeably increased viscosity causes the chelate signals to broaden into the spectral noise. The spectrum of an equimolar mixture of uranyl nitrate and 2′-deoxy-5′-AMP (5′-dAMP) is almost identical with the spectrum of 5′-dAMP at pD 10. Finally, in equimolar mixture the uranyl group is kept soluble at pD 10 by ribose phosphate but not by ribose. Unfortunately, the spectrum of the uranyl–ribose phosphate chelate could not be studied because lyophilization caused decomposition of the ribose moiety as evidenced by a color change of the mixture from yellow to brown.

It is physically impossible for a uranium atom to bind simultaneously to the phosphate group and both hydroxyl groups of a given 5′-AMP molecule. However, the use of Corey–Pauling–Koltun (CPK) space-filling atomic models shows that the dimeric sandwich-type structure **1** is geometrically feasible. In this di-



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nuclear structure each of the two uranium atoms, U_I and U_{II}, binds simultaneously to the 2′- and 3′-oxygen atoms of one 5′-AMP molecule and to a phosphate oxygen atom and the 3′-oxygen atom of the other 5′-AMP molecule. Both hydroxyl protons have been removed in formulating structure **1** because 4 moles of base is required to raise the pD of an equimolar U-AMP mixture to ~10. The second uranyl group in the higher complex (*i.e.*, higher than 1:1), shown in the previous section to be present in a 2:1 U:AMP mixture, must be chelated by the two phosphate oxygen atoms shown uncomplexed in structure **1**.

The Causes of Uranium-Induced Chemical Shifts in the Chelate Spectrum. The influence of the uranyl groups in the U-AMP chelate on the chemical shift of a ribose proton should be attributable to one or more of the following factors: (i) the magnetic anisotropy of the uranyl group; (ii) the electric field effect of the positively charged uranium atom; and (iii) the electron-withdrawing nature of the uranium if it binds covalently to a ligand atom.

The magnetic anisotropy effect is expressed by McConnell's equation[16]

$$\sigma_m = (1/3)R^{-3}\Delta\chi(1 - 3\cos^2\theta)$$

where σ_m is the chemical shift of a ribose proton induced by the anisotropy of one uranyl group, R is the distance between the proton and the uranium atom, $\Delta\chi$ is the magnetic susceptibility of a uranyl group (*i.e.*, uranyl ion formula weight divided by Avogadro's number), and θ is the angle between the long axis of the uranyl group and the line joining the proton and the uranium atom.

In Table I we have presented the results of applying this equation to each ribose proton of U-AMP, taking into account that each proton is influenced by both uranium atoms of the dimeric chelate. Thus, for a given proton, $\sigma_{m,I}$ and $\sigma_{m,II}$ refer, respectively, to the calculated magnetic anisotropy contributions of uranyl ions I and II to the chemical shift of that proton. Subscripts I and II are also used to indicate to which uranyl ion the R and θ values refer. These values of R and θ were estimated from the CPK molecular model of structure **1**. These values are probably no better than 0.5 cm and 5°, respectively, but we believe that our conclusions do not require any greater accuracy. The $\Delta\chi$ used was the value 2.74×10^{-28} calculated by Siddall and Prohaska.[17]

The new quantity σ^*_{expt} for a given proton is the difference between the chemical shifts of that proton in the 0.1 *M* U-AMP spectrum and in the 0.1 *M* 5′-AMP spectrum. For each proton σ^*_{expt} is positive because we are using the convention that the chemical shift is positive on the low-field side of the reference signal. The quantity Δ in the final column equals $\sigma^*_{expt} - (\sigma_{m,I} + \sigma_{m,II})$ and is our estimate of that part of the uranium-induced chemical shift which is attributable to the electric field effect of the uranyl group plus the electron-withdrawing action of this group.

(15) This conclusion does not contradict pH titration evidence presented in our previous paper[4] for binding of uranyl ion to the adenine ring at pH <~4.5, for there is no reason to expect the same type of chelation at pH 4.5 and 10, especially since, as will be discussed, the ionization of the protons of the ribose hydroxyl groups are involved in the chelation at the higher pH.

(16) H. M. McConnell, *J. Chem. Phys.*, 27, 226 (1957).

(17) T. H. Siddall, III, and C. A. Prohaska, *J. Am. Chem. Soc.*, **84**, 3467 (1962).

The chemical shift of a proton produced by the electric field, E, of a point charge at a distance R cm from the proton has been shown by Buckingham[18] to be equal to -1.5×10^{-18} $[10^{-10}R^{-2}E + (E^2/2)]$. It seems pointless to attempt to use this equation to calculate the electric field effect of a uranyl group on a proton of U-AMP, since the fact that each uranium atom is completely surrounded by oxygen atoms makes it impossible to estimate even crudely the effective uranium charge to be used in such a calculation. Even without calculations, however, we conclude that this effect is relatively unimportant in U-AMP since the uranium-induced shift of $H_{1'}$ is only 0.03 ppm despite the fact that $H_{1'}$ is only 3.6 cm from a uranium atom. No proton is significantly closer to a uranium atom than this distance, nor is any proton less "screened" from the uranium atom than is $H_{1'}$.

The small Δ value, 0.15 ppm, for $H_{1'}$ in Table I indicates that the electron-withdrawing action of the uranyl ion also does not seriously affect $H_{1'}$. However, the very large Δ values for $H_{2'}$ (5.07 ppm), $H_{3'}$ (3.04 ppm), $H_{5'}$ (1.22 ppm), and $H_{5''}$ (1.14 ppm) can only be attributed to the electron-withdrawing action of the uranium atoms. The effect on $H_{2'}$ and $H_{3'}$ results from the binding of uranium to the two ribose hydroxyl oxygens. The effect on $H_{5'}$ and $H_{5''}$ is due to the binding of uranium to a phosphate oxygen with the effect being transmitted through the phosphate group to the methylene group. Admittedly, the choice of which methylene proton is $H_{5'}$ and which is $H_{5''}$ was made arbitrarily. It seemed most reasonable that their Δ values should be almost equal, rather than the alternative which would make their Δ values 1.85 and 0.51 ppm, since the electron-withdrawing action should be about the same on each of the methylene protons.

(18) A. D. Buckingham, *Can. J. Chem.*, **38**, 300 (1960).

The difference between the Δ values of $H_{2'}$ and $H_{3'}$ means that the uranium withdraws more electronic charge from $O_{2'}$ than from $O_{3'}$ and, hence, implies that the $U-O_{3'}$ bonds are less covalent than the $U-O_{2'}$ bonds. We can suggest two possible explanations for this difference. One, the mutual repulsion of the positively charged uranium atoms and the mutual repulsion of the negatively charged $O_{3'}$ atoms would tend to increase the $U-O_{3'}$ bond distance and, thus, to make the $U-O_{3'}$ bonds less covalent than the $U-O_{2'}$ bonds. Alternatively, the $U-O_{3'}$ bonds would be longer than the $U-O_{2'}$ bonds if the $C_{3'}$ atom were out of plane,[19] in an *endo* conformation, with respect to the ribose ring. In fact, adopting a $C_{3'}$-*endo* conformation would probably also decrease the difference between the Δ values of $H_{2'}$ and $H_{3'}$. A similar Δ difference is shown by the U-ATP complex, but we believe its structure negates our first explanation. Hence, we presently favor the second explanation. The U-ATP studies will be described in a subsequent paper.

The Δ value of 0.42 for $H_{4'}$, being larger than the $H_{1'}$ value of 0.15, would seem to imply that the electron-withdrawing action of the uranium atoms on $H_{4'}$ is significantly large. If this were true, it would have to be due to transmission to $H_{4'}$ of the inductive effect of the uranium atom attached to phosphate, since Δ for $H_{3'}$ is less than for $H_{2'}$. However, it is quite possible that the difference in the Δ values of $H_{1'}$ and $H_{4'}$ are within the error of our calculations. It can be seen in Prohaska and Siddall's graph[17] relating the magnetic field around the uranyl group to the geometric coordinates that an error in our estimated coordinates would be most serious near a θ of 55°, *i.e.*, near our θ_I for H_1 and θ_{II} for $H_{4'}$.

(19) The nonplanarity of nucleotide pentose rings has been discussed earlier.[7,20,21]

(20) C. D. Jardetzky, *J. Am. Chem. Soc.*, **84**, 62 (1962).

(21) A. E. V. Haschemeyer and A. Rich, *J. Mol. Biol.*, **27**, 369 (1967).