

Synthetic Applications of *N-N* Linked Heterocycles. Part 17.¹ The Crystal and Molecular Structures of *N*-(4-Oxopyridin-1-yl)pyridinium Tetrafluoroborate, and its 2,6-Dimethyl Analogue: Evidence for Steric Hindrance to Approach by Nucleophiles at the Pyridinium α Positions in the Latter, and a Note of Protonation Effects on Chemical Shifts

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The crystal structures of the title compounds (1) and (2) have been determined by X-ray diffraction; both are monoclinic with $Z = 4$, and have space groups and unit cell dimensions, respectively, $P2_1/c$, $a = 10.876(2)$, $b = 8.913(2)$, $c = 12.805(4)$ Å, $\beta = 112.16(2)^\circ$, and $C2/m$, $a = 22.390(5)$, $b = 6.944(2)$, $c = 9.330(2)$ Å, $\beta = 98.96(1)^\circ$. Both structures were determined by the Patterson method; refinements were to R 0.057 for 637 independent reflections in (1) and to R 0.079 for 1 065 in the dimethyl analogue (2). The *N-N* bond lengths, and the torsion angles between the ring planes, are, respectively, 1.417(7) Å and $74(3)^\circ$, and 1.411(5) Å and 90° ; the positions of the methyl groups in (2) effectively shield the pyridinium α -positions from attack by bulky groups, accounting for the observed regiospecific addition of nucleophiles at the γ -position. U.v., and ^1H and ^{13}C n.m.r. spectra in both aqueous and acidic media, for compounds (1), (2), and the 2-methyl analogue (3), while providing no evidence for steric interactions between the methyl groups and the pyridinium ring, demonstrate the electronegativity of both rings. In acid solution protonation occurs at the carbonyl oxygen atoms; protonation effects on ^1H , ^{13}C , and ^{15}N chemical shifts are discussed.

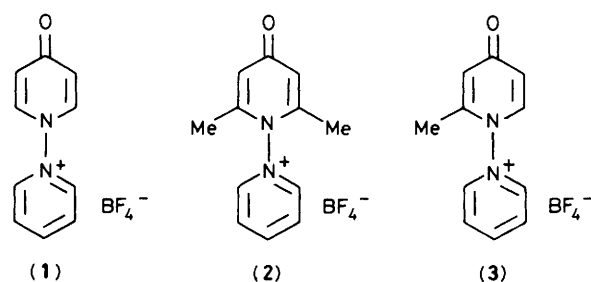
In earlier parts of this series we demonstrated that 4-substituted pyridines may be prepared regiospecifically in high yields by the attack of a wide range of nucleophiles on the 4-oxopyridinyl-pyridinium salt (2).² Since similar regiospecificity was not shown by the dimethyl analogue (1), it appeared that the methyl groups in the pyridone moiety of compound (2) were sterically shielding the 2- and 6-position of the pyridinium ring, thus directing nucleophiles to the 4-position. It was therefore of interest to determine the structures of the salts (1) and (2) by X-ray diffraction in order to establish the effect of the methyl groups on molecular geometry.†

Possible steric interactions between the methyl groups and the pyridinium ring may also be probed by ^{13}C n.m.r. spectroscopy, and conjugation between the two rings by u.v. spectroscopy. These salts were also known to be protonated in strongly acidic media;³ the site of protonation, and its effect on ^1H and ^{13}C chemical shifts, are of additional interest. Thus, u.v. and ^1H and ^{13}C n.m.r. spectra of the salts (1) and (2), and of the monomethyl analogue (3) for comparison, have also been recorded, both in aqueous and in 18% hydrochloric acid solutions. We have also examined the ^{15}N n.m.r. spectra of 4-pyridone and its cation.

Experimental

Compounds (1) and (2),³ and (3)⁴ were prepared as described previously; crystals of the salts (1) and (2) were grown from 95% ethanol. Compound (2) formed a *monohydrate*, m.p. $> 200^\circ\text{C}$ (Found: C, 47.2; H, 4.7; N, 9.3. $\text{C}_{12}\text{H}_{13}\text{BF}_4\text{N}_2\text{O}\cdot\text{H}_2\text{O}$ requires C, 47.1; H, 4.9; N, 9.2%).

Crystal Data.—**Compound (1).** $\text{C}_{10}\text{H}_9\text{BF}_4\text{N}_2\text{O}$, $M = 260.0$. Monoclinic, space group $P2_1/c$ (No. 14), $a = 10.876(2)$, $b =$



$8.913(2)$, $c = 12.805(4)$ Å, $\beta = 112.16(2)^\circ$, $U = 1 149.6(5)$ Å³, $Z = 4$, $D_c = 1.502$ g cm⁻³, Mo- K_α radiation, $\lambda = 0.710 69$ Å, $\mu(\text{Mo-}K_\alpha) = 1.54$ cm⁻¹.

Intensity data were collected from a crystal of dimensions $0.26 \times 0.24 \times 0.11$ mm in a Syntex $P2_1$ diffractometer using the $\theta-2\theta$ scanning technique with scans ranging from 0.9° below the K_α peak to 0.9° above the K_α peak, and a scan rate of 1° min^{-1} ; the background was counted for one half of the scan time at each extreme. All reflections within the $hk \pm l$ quadrants extending to $2\theta = 40^\circ$ were measured. Three check reflections were monitored continually and gave no indication of intensity loss during data collection. A total of 1 083 independent reflections were obtained, of which 637 had a net intensity greater than $3\sigma(I)$. No correction was made for absorption.

Compound (2). $\text{C}_{12}\text{H}_{15}\text{BF}_4\text{N}_2\text{O}_2$, $M = 306.1$. Monoclinic, space group $C2/m$ (No. 12), $a = 22.390(5)$, $b = 6.944(2)$, $c = 9.330(2)$ Å, $\beta = 98.96(1)^\circ$, $U = 1 432.9(5)$ Å³, $Z = 4$, $D_c = 1.41$ g cm⁻³, Cu- K_α radiation, $\lambda = 1.541 8$ Å, $\mu(\text{Cu-}K_\alpha) = 8.23$ cm⁻¹.

Intensity data were collected from a crystal of dimensions $0.47 \times 0.25 \times 0.16$ mm on a Datex-automated General Electric XRD-5 diffractometer using $\theta-2\theta$ scans at a scanning speed of 1° min^{-1} (in 2θ); the background was counted for 30 s at each extreme. The scan ranges were adjusted to account for

† To facilitate comparison of X-ray and spectroscopic data, the crystallographic numbering system as shown in Figures 1 and 2 is used throughout this paper.

Table 1. Fractional atomic co-ordinates ($\times 10^4$) for non-hydrogen atoms for compound (1) with e.s.d.s in parentheses

Atom	x	y	z
N(1)	6 897(4)	3 639(6)	1 536(4)
N(2)	7 523(5)	3 739(6)	2 725(4)
C(1)	5 975(6)	2 542(6)	1 074(5)
C(2)	5 419(5)	2 438(7)	-50(5)
C(3)	5 763(6)	3 411(7)	-779(5)
C(4)	6 697(6)	4 550(7)	-232(5)
C(5)	7 252(5)	4 640(7)	890(5)
C(6)	7 160(6)	4 829(7)	3 239(6)
C(7)	7 783(7)	4 928(8)	4 409(6)
C(8)	8 707(7)	3 901(9)	4 980(5)
C(7')	9 036(6)	2 783(7)	4 410(5)
C(6')	8 428(6)	2 701(7)	3 249(5)
O(1)	5 281(4)	3 266(5)	-1 831(3)
B	1 377(14)	3 626(16)	2 435(11)
F(1) ^a	2 380(20)	4 664(18)	3 140(11)
F(2) ^a	302(25)	4 168(28)	1 945(23)
F(3) ^a	1 733(21)	2 834(29)	1 693(21)
F(4) ^b	1 476(20)	2 691(19)	3 311(20)
F(1') ^a	2 407(18)	3 904(35)	3 108(18)
F(2') ^b	353(19)	4 610(20)	2 433(19)
F(3') ^b	1 499(26)	3 855(29)	1 472(14)
F(4') ^b	888(14)	2 215(12)	2 369(19)

^a Occupancy factor 0.46(2). ^b Occupancy factor 0.54(2).

α_1 - α_2 splitting. All reflections within one quadrant of the sphere extending to $2\theta = 130^\circ$ were measured. Three check reflections were monitored continually and each indicated a gradual drop in intensity; at the end this varied from 10 to 18%, the crystal having turned brown. A total of 1 329 independent reflections were obtained, of which 1 065 had intensity greater than $3\sigma(I)$. No correction was made for absorption.

Solution and Refinement.—Both structures were determined by the Patterson method, and refined by full-matrix least-squares procedures, the quantity minimised being $\sum w(F_o^2 - F_c^2)^2$ with weight $w = 1/\sigma^2(F_o^2)$. Calculations were carried out at the California Institute of Technology, using the CRYM system.⁵ Atomic scattering factors were taken from International Tables.⁶

Compound (1). The disordered tetrafluoroborate ion was refined as two interlocking groups with the boron atom common to both; the isotropic temperature factor for boron was fixed at $B = 8.0 \text{ \AA}^2$. All hydrogen atoms were kept at their calculated positions with isotropic temperature factors $B = 4.0 \text{ \AA}^2$. The final R index for 637 reflections was 0.057; the 'goodness of fit', $[\sum w(F_o^2 - F_c^2)^2/(m - s)]^{1/2} = 1.80$, where $m = 1 083$ measurements and $s = 193$ parameters. Fractional atomic co-ordinates for non-hydrogen atoms are given in Table 1, and bond distances and angles in Table 2.

Compound (2). The fluorine atoms in the tetrafluoroborate ion showed large anisotropic effects; the water molecule was disordered. The final R index for 1 065 reflections was 0.079, and the 'goodness of fit' for 1 329 measurements and 163 parameters was 8.0. Fractional atomic co-ordinates for non-hydrogen atoms are given in Table 3, and bond distances and angles in Table 4.

Final observed and calculated structure factors were obtained, and thermal parameters for both compounds are available as a Supplementary Publication (SUP No. 56136, 3 pp.).*

* For details of the Supplementary Publications Scheme, see Instructions for Authors, *J. Chem. Soc., Perkin Trans. 2*, 1985, Issue 1. Structure factors are available from the editorial office on request.

Table 2. Bond distances and angles for compound (1) with e.s.d.s in parentheses

(a) Distances (\AA)			
N(1)-N(2)	1.417(7)	C(3)-O(1)	1.254(7)
N(1)-C(1)	1.365(8)	N(2)-C(6)	1.314(8)
C(1)-C(2)	1.338(8)	C(6)-C(7)	1.395(10)
C(2)-C(3)	1.424(8)	C(7)-C(8)	1.352(10)
C(3)-C(4)	1.420(9)	C(8)-C(7')	1.361(10)
C(4)-C(5)	1.334(9)	C(7')-C(6')	1.383(9)
C(5)-N(1)	1.368(8)	C(6')-N(2)	1.333(8)
B-F(1)	1.456(22)	B-F(1')	1.153(28)
B-F(2)	1.200(30)	B-F(2')	1.418(25)
B-F(3)	1.351(29)	B-F(3')	1.305(28)
B-F(4)	1.369(26)	B-F(4')	1.356(22)
(b) Angles ($^\circ$)			
N(1)-C(1)-C(2)	118.4(5)	N(2)-N(1)-C(1)	119.2(5)
C(1)-C(2)-C(3)	122.7(6)	N(1)-N(2)-C(6)	118.1(5)
C(2)-C(3)-O(1)	122.3(6)	N(1)-N(2)-C(6')	117.5(5)
O(1)-C(3)-C(4)	122.4(6)	C(6)-N(2)-C(6')	124.4(6)
C(2)-C(3)-C(4)	115.3(5)	N(2)-C(6)-C(7)	118.0(6)
C(3)-C(4)-C(5)	121.5(6)	C(6)-C(7)-C(8)	119.9(6)
C(4)-C(5)-N(1)	119.7(6)	C(7)-C(8)-C(7')	119.9(7)
C(5)-N(1)-C(1)	122.3(5)	C(8)-C(7)-C(6')	120.0(6)
C(5)-N(1)-N(2)	118.5(5)	C(7')-C(6')-N(2)	117.9(6)
F(1)-B-F(2)	115(2)	F(1')-B-F(2')	114(2)
F(1)-B-F(3)	115(2)	F(1')-B-F(3')	105(2)
F(1)-B-F(4)	94(1)	F(1')-B-F(4')	120(2)
F(2)-B-F(3)	109(2)	F(2')-B-F(3')	105(2)
F(2)-B-F(4)	116(2)	F(2')-B-F(4')	107(1)
F(3)-B-F(4)	108(2)	F(3')-B-F(4')	105(2)

Table 3. Fractional atomic co-ordinates ($\times 10^4$) for non-hydrogen atoms in compound (2) with e.s.d.s in parentheses

Atom	x	y	z
N(1)	1 709(2)	0	3 688(4)
N(2)	1 094(2)	0	3 060(4)
C(1)	2 137(2)	0	2 778(5)
C(2)	2 724(2)	0	3 386(5)
C(3)	2 910(2)	0	4 917(5)
C(4)	2 447(2)	0	5 779(5)
C(5)	1 846(2)	0	5 188(5)
C(6)	821(2)	1 695(5)	2 749(4)
C(7)	220(2)	1 708(6)	2 155(5)
C(8)	-77(2)	0	1 866(6)
C(9)	1 931(2)	0	1 172(5)
C(10)	1 346(2)	0	6 060(6)
O(1)	3 463(1)	0	5 482(4)
O(2) ^a	4 479(4)	670(16)	4 145(6)
B	3 796(3)	0	251(7)
F(1)	3 289(2)	0	-745(5)
F(2)	4 254(3)	0	-410(8)
F(3)	3 811(2)	1 598(4)	1 074(3)

^a Occupancy factor 0.5.

Spectroscopic Data.—U.v. spectra (*ca.* 8×10^{-5} M in water or 18% HCl) were recorded on a Beckmann Acta CIII spectrophotometer; results are given in Table 5. ¹H N.m.r. (89.61 MHz; digital resolution ± 0.005 p.p.m.) and ¹³C n.m.r. (22.53 MHz; digital resolution ± 0.03 p.p.m.) spectra were run on a JEOL FX-90Q spectrometer. Solutions were 0.1M in D₂O or in 18% DCl-D₂O; DSS was used as the internal reference. Results are given in Tables 6 and 7. ¹⁵N N.m.r. (30.41 MHz) spectra were run on a Nicolet NT300 spectrometer, using neat liquid nitromethane as the external reference.

Table 4. Bond distances and angles for compound (2) with e.s.d.s in parentheses

(a) Distances (Å)			
N(1)–N(2)	1.411(5)	C(1)–C(9)	1.498(6)
N(1)–C(1)	1.376(6)	C(5)–C(10)	1.483(7)
C(1)–C(2)	1.346(6)	C(3)–O(1)	1.268(6)
C(2)–C(3)	1.425(6)	N(2)–C(6)	1.338(5)
C(3)–C(4)	1.407(6)	C(6)–C(7)	1.373(6)
C(4)–C(5)	1.373(7)	C(7)–C(8)	1.365(7)
C(5)–N(1)	1.385(6)		
B–F(1)	1.350(7)	B–F(3)	1.347(7)
B–F(2)	1.273(9)		
(b) Angles (°)			
N(1)–C(1)–C(2)	117.9(4)	C(10)–C(5)–N(1)	119.2(4)
N(1)–C(1)–C(9)	118.8(4)	C(5)–N(1)–C(1)	123.9(4)
C(9)–C(1)–C(2)	123.3(4)	C(5)–N(1)–N(2)	117.8(3)
C(1)–C(2)–C(3)	122.4(4)	C(1)–N(1)–N(2)	118.3(3)
C(2)–C(3)–O(1)	122.0(4)	N(1)–N(2)–C(6)	118.3(3)
C(2)–C(3)–C(4)	116.5(4)	C(6)–N(2)–C(6')	123.3(4)
O(1)–C(3)–C(4)	121.4(4)	N(2)–C(6)–C(7)	118.7(4)
C(3)–C(4)–C(5)	122.3(4)	C(6)–C(7)–C(8)	119.3(4)
C(4)–C(5)–C(10)	123.8(4)	C(7)–C(8)–C(7')	120.6(5)
C(4)–C(5)–N(1)	117.0(4)		
F(1)–B–F(2)	108.6(5)	F(2)–B–F(3)	109.2(5)
F(1)–B–F(3)	109.6(6)	F(3)–B–F(3')	111.0(5)

Table 5. U.v. spectroscopic data for the compounds (1)–(3)

Compound	$\lambda_{\max.}/\text{nm}$ ($\epsilon/\text{dm}^3 \text{ mol}^{-1} \text{ cm}^{-1}$) ^a					
	In H ₂ O			In 18% HCl		
(1)	204 (14 050)	259 (27 950)	290 ^b (7 950)	208 (15 700)	257.5 (19 750)	
(2)	211 (15 350)	259 (24 890)	290 ^b (1 350)	208 (18 250)	253 (20 250)	
(3)	208.5 (14 750)	260.5 (24 200)	295 ^b (2 400)	209 (17 050)	255 (20 200)	

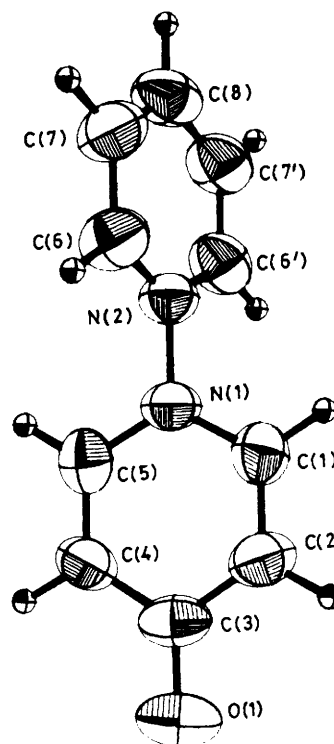
^a Solutions *ca.* 8×10^{-5} M. ^b Inflection.

Results and Discussion

Crystal Structures of the Salts (1) and (2).—*The cations.* ORTEP Plots for the cations of salts (1) and (2) are shown in Figures 1 and 2 respectively. Bond distances and angles (Tables 2 and 4) for the pyridone rings are consistent with other structures containing these moieties.⁷ Further, the atoms in each pyridone ring are coplanar to within ± 0.02 Å, while those for the pyridinium rings are within ± 0.01 Å.

However, a comparison with data from seven other pyridinium salts⁸ reveals that the angles associated with N(2), C(6), and C(6') in the structures (1) and (2)[†] deviate significantly from analogous published values; further, the bond distances N(2)–C(6) and N(2)–C(6') are at the short end of the observed range. Thus, the corresponding mean angles (°) and distances (Å) with standard deviations, taken from reference 8, are: C(6)–N(2)–C(6'), 120.5(5); N(2)–C(6)–C(7), 120.3(9); N(2)–C(6')–C(7'), 120.9(5); N(2)–C(6), 1.344(7); and N(2)–C(6'), 1.340(13). Similar variations in bond angles and lengths have

[†] Space group symmetry requires the pyridinium ring in compound (2) to be symmetrical about a plane through N(2) and C(8), and perpendicular to the ring.

**Figure 1.** ORTEP drawing for compound (1) showing the atom numbering scheme

been observed around the carbon atom bearing non-conjugating electronegative groups X in monosubstituted benzenes. They have been rationalised in terms of small changes in the hybridisation state of the carbon atom such that an increase in *p* character of the C–X bond results in some lengthening.⁹ The pyridone substituents attached to N(2) in the salts (1) and (2) are quite strongly electronegative, as demonstrated by the pyridine ring-opening reactions observed in the presence of strong Brønsted bases.^{3,10} An increase in *p* character in the N(1)–N(2) bond would accommodate the above deviations, the concomitant increase in *s* character in the N(2)–C(6) and N(2)–C(6') bonds resulting both in their shortening, and in the opening of the C(6)–N(2)–C(6') angles. Some closing of the N(2)–C(6)–C(7) and N(2)–C(6')–C(7') angles would follow to maintain the ring geometry. There is also evidence that lengthening has occurred in the N(1)–N(2) bonds in structures (1) and (2) (1.417 and 1.411 Å, respectively). For example, while the N–N distance in phenylhydrazine hydrochloride is 1.432 Å,¹¹ the values found in three other N–N linked heterocycles having *sp*²-hybridised nitrogen atoms are 1.396,¹² 1.372,¹³ and 1.38 Å.¹⁴

The other parameters of interest in the two dications are the dihedral angles between the least-squares ring planes, and for compound (2) the positions of the C-methyl groups and associated bond angles which may show evidence of steric compression. The dihedral angles between the ring planes in compound (1) is 74°, a value larger than anticipated, and probably a compromise between the interactions H(1)⋯H(6') (2.98 Å) and H(5)⋯H(6) (2.99 Å), and crystal packing forces. For biphenyl (inter-ring distance 1.493 Å) the dihedral angle is 0°,¹⁵ while for the *N*-phenylpyridinium cation (inter-ring distance 1.464 Å) it is *ca.* 47°.¹⁶

In the dimethyl compound (2), the dihedral angle is 90° as required by space group symmetry. The distances of the methyl hydrogen atoms H(9B) and H(10B) from a line perpendicular to

Table 6. ^1H N.m.r. data for the salts (1)—(3)

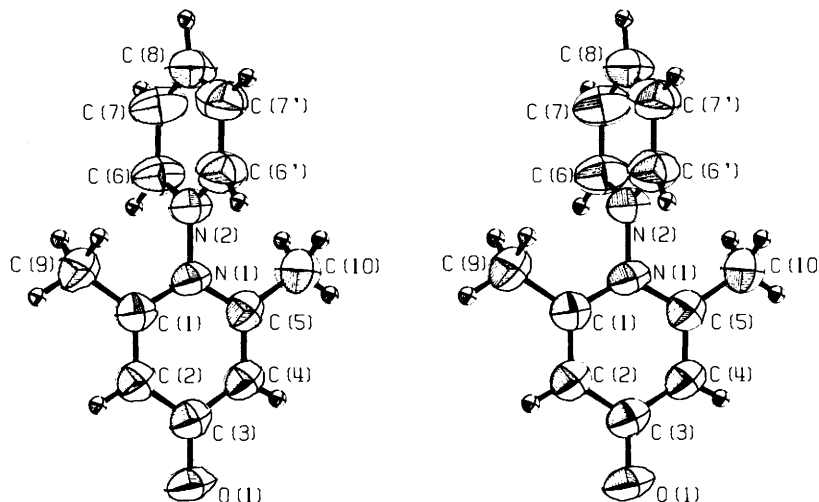
Compound	Solvent ^b	$\delta_{\text{H}}^{\text{a}}$						
		H(1) ^c	H(2)	H(4)	H(5) ^d	H(6)	H(7)	H(8)
(1)	A	8.290	6.698	6.698	8.290	9.460	8.427	8.979
(1)	B	9.202	7.646	7.646	9.202	9.662	8.561	9.125
(2)	A	(2.109)	6.542	6.542	(2.109)	9.457	8.564	9.115
(2)	B	(2.453)	7.484	7.484	(2.453)	9.726	8.722	9.276
(3)	A	(2.153)	6.581	6.621	8.178	9.443	8.495	9.052
(3)	B	(2.521)	7.602	7.557	9.109	9.689	8.642	9.206

^a At 89.61 MHz; standard DSS; digital resolution ± 0.005 p.p.m. ^b Solutions 0.1M; A = D_2O , B = 18% $\text{DCl-D}_2\text{O}$. ^c Values in parentheses are for H(9). ^d Values in parentheses are for H(10).

Table 7. ^{13}C N.m.r. data for the salts (1)—(3)

Compound	Solvent ^b	$\delta_{\text{C}} (^1J_{\text{CH}}/\text{Hz})^{\text{a}}$									
		C(1)	C(2)	C(3)	C(4)	C(5)	C(6)	C(7)	C(8)	C(9)	C(10)
(1)	A	142.48 (190.9)	120.48 (170.6)	183.70 (7.88) ^c	120.48 (170.6)	142.48 (190.9)	147.68 (202.1)	132.56 (182.6)	153.15 (176.0)		
(1)	B	146.54 (197.8)	118.53 (178.8)	177.80	118.53 (178.8)	146.54 (197.8)	146.97 (203.9)	132.73 (183.1)	154.40 (177.0)		
(2)	A	152.23	119.56 (169.7)	183.60	119.56 (169.7)	152.23	149.36 (199.6)	133.70 (182.7)	154.45 (177.0)	19.72 (133.8)	19.72 (133.8)
(2)	B	157.59	117.50 (176.4)	175.74 (2.75) ^d	117.50 (176.4)	157.59	147.41 (202.0)	134.19 (180.7)	155.32 (177.6)	21.18 (133.1)	21.18 (133.1)
(3)	A	151.90	119.40 (172.1)	183.81 (7.93) ^c	120.27 (169.7)	143.24 (190.1)	148.82 (200.2)	133.11 (182.8)	153.96 (176.4)	19.29 (131.8)	
(3)	B	157.70	117.07 (178.2)	176.66 (7.93) ^c	118.75 (175.8)	146.81 (195.9)	147.30 (199.6)	133.43 (181.3)	154.83 (177.0)	20.86 (133.1)	

^a At 22.53 MHz; standard DSS; digital resolution ± 0.03 p.p.m., ± 0.6 Hz. ^b Solutions 0.1M; A = D_2O ; B = 18% $\text{DCl-D}_2\text{O}$. ^c $^3J_{\text{CH}}$. ^d $^2J_{\text{CH}}$.

**Figure 2.** ORTEP drawing for compound (2) showing the atom numbering scheme

the pyridinium ring and passing through C(6) are, respectively, 1.37 and 1.34 Å. Assuming a van der Waals radius for hydrogen of 1.20 Å,¹⁷ this accounts very nicely for the shielding by the methyl groups of C(6) [and C(6')] to the approach of nucleophiles from above or below the ring. Interestingly, the exocyclic angles about the methyl groups are very similar to those reported in another 2,6-dimethyl-4-pyridone derivative,^{7a} suggesting that there is very little steric interaction between the methyl groups and the pyridinium ring in compound (2).

Other structural features. The tetrafluoroborate anion in the

salt (1) (not shown) has a pseudo-cubic configuration, arising from two-fold disorder; each fluorine atom occupies two different sites, having occupancy factors 0.46 and 0.54, respectively (Table 1). This same phenomenon has been reported in another pyridinium tetrafluoroborate.¹⁸ The fluorine atoms in the anions of both salts also show large anisotropic thermal motions, as evidenced by the magnitudes of the relevant thermal parameters (Supplementary Publication).

The water molecule in structure (2) is also disordered between two sites having equal (0.5) occupancies. Short intermolecular

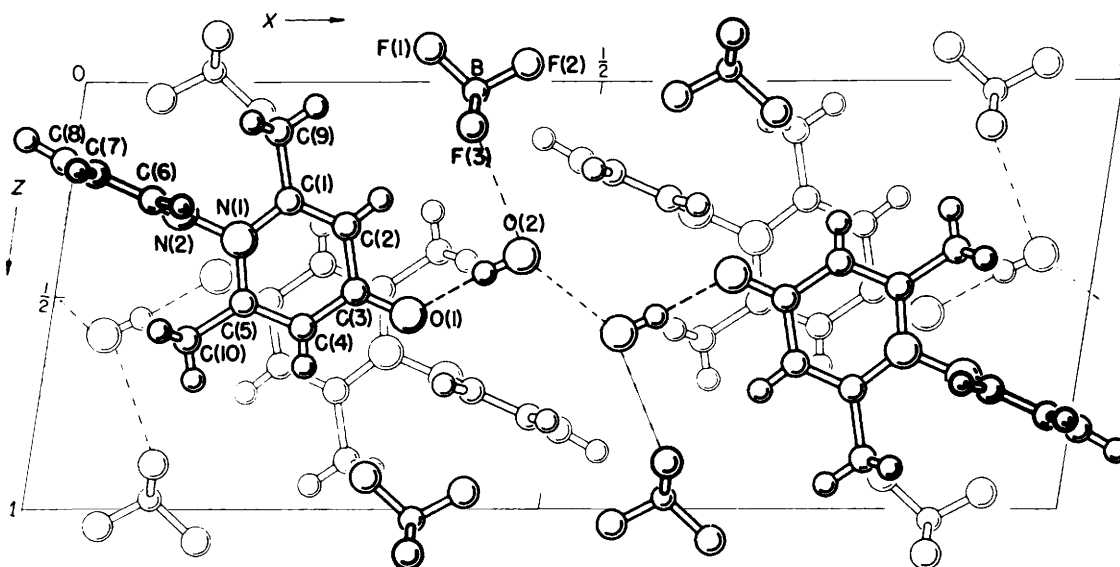


Figure 3. Unit cell packing diagram for compound (2) showing positions of the tetrafluoroborate ions and water molecules, and the hydrogen bonding contacts

hydrogen bonding distances involving this molecule are: O(2)···O(1), 2.800 Å; O(2)···F(3), 3.088 Å; O(2)···O(2) (at $1-x, y, 1-z$), 2.612 Å; and O(2)···O(2) (at $1-x, -y, 1-z$), 2.772 Å. The arrangement in the unit cell of compound (2) is shown in the packing diagram (Figure 3).

Spectroscopic Data.—**Ultraviolet.** Batts and Madeley¹⁹ have shown that for a number of *N*-substituted 4-pyridones the principal absorption (260–270 nm) at pH 7 is shifted to a shorter wavelength by 15–20 nm, with an associated *ca.* two-fold decrease in ϵ_{\max} , on lowering the pH to 0.5. The changes are associated with protonation at the carbonyl group, and are larger for more basic compounds. The data in Table 5 show similar, though smaller, changes to the peak near 260 nm on going from aqueous to 18% HCl solutions, and suggest that compounds (1)–(3), while of very low basicity, are also protonated at the carbonyl group.

The other notable feature is the shoulder near 290 nm which decreases in intensity in the series (1) → (3) → (2), and disappears in hydrochloric acid solution. While it may originate from limited conjugation between the two rings, it could also arise from limited reversible attack by water at C(6) followed by electrocyclic ring-opening. The latter process would be suppressed by adding acid.

¹H N.m.r. Data are included in Table 6. Chemical shifts (in D₂O) for the protons corresponding to H(1) and H(2) in *N*-methyl-4-pyridone are, respectively, 7.87 and 6.57 p.p.m., while for those corresponding to H(9) and H(2) in 1,2,6-trimethyl-4-pyridone values are 2.33 and 6.12 p.p.m.¹⁹ For *N*-methylpyridinium iodide, signals corresponding to H(6), H(7), and H(8) are, respectively, at 9.18, 8.26, and 8.72 p.p.m.²⁰

All signals in compounds (1) and (2) in D₂O, with the exception of the methyl signals H(9), show a downfield shift relative to the above model compounds, reflecting the greater electronegativity of the *N*-substituents from the point of view of both the pyridone and the pyridinium rings. The high-field shift in the methyl signal in compound (2) [and (3)] probably arises from anisotropic shielding by the aromatic pyridinium ring.

In 18% DCl–D₂O, all signals in the three compounds are shifted downfield relative to values in D₂O solution: *ca.* 1 p.p.m. for pyridone ring protons, *ca.* 0.35 p.p.m. for methyl groups, and

smaller shifts for the pyridinium ring. The shifts are again consistent with an increase in positive charge on the pyridone rings, arising from protonation at the carbonyl group.

¹³C N.m.r. of neutral species. The signal assignments for compounds (1)–(3) are supported by the shifts of 4-pyridone and the *N*-methylpyridinium cation. 4-Pyridone shows ¹³C chemical shifts at 140.0, 116.2, and 176.6 p.p.m.²¹ for the carbon atoms corresponding to C(1), C(2), and C(3) of compounds (1)–(3), respectively. The *N*-methylpyridinium cation likewise shows signals at 146.47, 129.21, and 146.47 p.p.m.²² for the atoms corresponding to C(6), C(7), and C(8). Superficially, all carbon atoms signals for compound (1) in D₂O (Table 7) are to lower field than the analogous signals for the model compounds, and consistent with an increase in positive charge on both rings. However, $\Delta\delta$ for those carbon atoms α to ring nitrogens is smaller than for other ring carbon atoms. This effect has been discussed for pyridinium salts.²³ A similar pattern is observed for the salts (2) and (3), except that C(1) in (3), and C(1) and C(5) in (2), show an additional shift due to methyl substitution; the magnitude (*ca.* 9–10 p.p.m.) is as expected, as is the small upfield shift at C(2) in (3) and C(2) and C(4) in (2) relative to compound (1). There is no evidence for steric compression of the methyl groups.

¹³C N.m.r. of protonated species. 4-Pyridones are known to be protonated at the oxygen atom.²⁴ Recent confirmation comes from the reported ¹³C n.m.r. study of the protonation of 2,6-dimethyl- γ -pyrone and related bases in superacid systems.²⁵ The C-3 and C-4 protonation shifts (–2.6 and –9.0 p.p.m.) of 4-pyridone strongly resemble those of *C-ortho* and *C-ipso* (–3.6 and –11.0 p.p.m.) for phenolate ion protonation.²⁶

The effect of protonation on the ¹³C chemical shifts in pyridines (Table 8) (C-2 upfield; C-3 and C-4 downfield) have been discussed and explained elsewhere.²³ We now confirm that the chemical shift changes on the protonation of 4-pyridone are quite different: C-2 downfield, and C-3 and especially C-4 upfield (Table 8). Precisely the same trends are found for the corresponding carbon atoms in the pyridone ring of the salts (1)–(3) on protonation (Table 6). In 18% DCl–D₂O the pyridinium carbon signals show only small changes, although these are consistently to high field for C(6).

In general, ¹J_{CH} increases with decreasing electron density on the carbon atom.²⁷ Increases of each of the ¹J_{CH} values for

Table 8. ^{13}C N.m.r. data^a for pyridine and 4-pyridone

Compound	Solvent	δ_{C} ($^1J_{\text{CH}}/\text{Hz}$)		
		C-2(C-6)	C-3(C-5)	C-4
4-Pyridone	D ₂ O	139.1 (180.1)	116.6 (167.1)	180.3
	18% DCI-D ₂ O	142.1 (189.0)	114.2 (171.4)	171.0
Pyridine	D ₂ O	148.5 (180.2)	124.2 (165.6)	137.1 (165.6)
	18% DCI-D ₂ O	141.2 (192.0)	127.7 (178.8)	147.5 (172.9)

^a Spectra run on a JEOL FX100 spectrometer; at 25.1 MHz; external standard 1,4-dioxane.

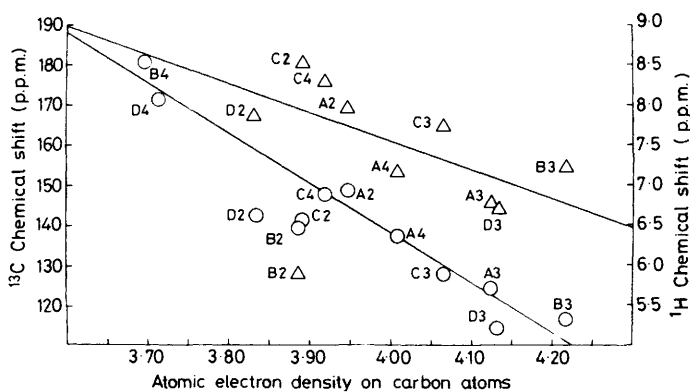


Figure 4. Plot of ^{13}C (O) and ^1H (Δ) chemical shifts (p.p.m.) for the 2-, 3-, and 4-position of: A, pyridine (in D₂O); B, 4-pyridone (in D₂O); C, pyridine (in 18% DCI-D₂O); and D, 4-pyridone (in 18% DCI-D₂O) versus atomic electron density on carbon atoms of pyridine, 4-pyridone, pyridinium cation, and 4-hydroxypyridinium cation, respectively

pyridine on protonation were reported previously;²⁸ our work confirms this [Δ^1J_{CH} 7–13 Hz], and shows that it also applies to both $^1J_{\text{CH}}$ values for 4-pyridone (Δ^1J_{CH} 4–9 Hz) (Table 8). For compounds (1)–(3) similar increases in $^1J_{\text{CH}}$ for the pyridone ring are found on protonation, while values for the pyridine ring, which already carries a positive charge, are but little affected by the remote protonation (Δ^1J_{CH} 1 Hz) (Table 7).

¹⁵N N.m.r. The ¹⁵N chemical shifts for 4-pyridone in D₂O (–227.1 p.p.m.), 18% DCI-D₂O (–204.3), and CF₃CO₂H (–206.8) show a downfield shift on protonation. By contrast, protonation of pyridine causes an upfield shift of 118 p.p.m.²⁹ However, work on peptides suggests that amide ¹⁵N resonances are shifted downfield on protonation.³⁰ We have confirmed this for dimethylformamide [neat –276.4 p.p.m.; in CF₃CO₂H (1:1), –266.1 p.p.m.].

Calculations. We attempted to explain these chemical shifts by correlation with MNDO (Figure 4) electron densities. Taking all the ^{13}C shifts together, plotting against the carbon electron densities gives a reasonable correlation ($r^2 = 0.878$): it is evident from Figure 4 that the major discrepancies arise from the carbon shifts α to the nitrogen atoms; indeed the correlation improves to 0.972 (line on graph) if these are omitted. The α -carbons are probably affected by anisotropy considerations.

A plot of the ^1H shifts against the hydrogen electron densities gives no correlation ($r^2 = 0.23$): a plot against the adjacent carbon electron density gives only a poor correlation ($r^2 = 0.592$ omitting point B2, see line on graph Figure 4).

The calculations thus resolve some of the apparent discrepancy of an upfield shift for the γ -carbon of 4-pyridone on protonation. Protonation of carbonyl oxygen atoms generally results in a large downfield shift by the carbon signal. Thus, δ_{C} for the carbonyl carbon atom in benzophenone, before and after protonation, is, respectively, 195.2 and 208.2 p.p.m.³¹

The present work now satisfactorily explains the analogous shift to high field found for the corresponding carbon signals in a series of 4-arylimino-2,6-dimethylpyrans on protonation at nitrogen.³²

Acknowledgements

Part of this work was supported by Research Grant No. GM-16966 from the National Institute of General Medical Sciences, USPHS to R. E. Marsh, whose help we gratefully acknowledge. We thank Mr. Ban Chi Chen for determining the ¹⁵N n.m.r. spectra.

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Received 9th July 1984; Paper 4/1180