Mechanisms for Photochemical Hydration of *N*-Substituted Pyridinium Ions

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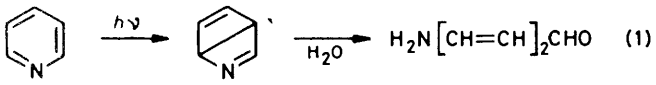
Photoinduced hydration of some pyridinium ions has been studied. Several pathways in the photohydration of quaternary pyridinium ions were observed. The substituents, especially at the nitrogen atom of the ring profoundly affect the reaction pathway, *i.e.* *N*-benzyl- and *N*-phenyl-pyridinium ions gave ring-cleaved ω-aminoaldehydes [*e.g.* (3)] *via* 2-hydroxy-1,2-dihydropyridines [*e.g.* (2)] (Type A), while *N*-methyl isomers afforded azabicyclo-[3.1.0]hex-3-en-2-ols (14) as reported by Kaplan (Type B). But exceptionally, *N*-methyl-3-carbamoylpyridinium ion (11h), which has an electron-withdrawing group, undergoes the Type A reaction. The Type A reaction clearly predominates over Type B, since nucleophiles can add in the dark to a pyridinium ion possessing an appropriate electron-withdrawing group in the ring.

PHOTOHYDRATION of the pyridinium ion, which does not have lone pair electrons on nitrogen, is different from that of free pyridine. The pyridinium ion resembles that of benzene, arising from π–π* excitation where hydration of the initially formed azoniabenzvalene yields azabicyclo-[3.1.0]hex-3-en-2-ol (14a).[1] By contrast, free pyridine undergoes *n*–π* excitation to give 2-azabicyclo[2.2.0]-hex-2,5-diene which is then hydrated to give ω-amino-pentadienal as shown in equation (1).[2,3] But *N*-



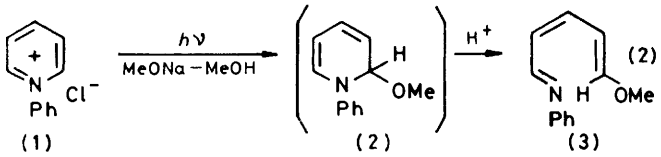
(1)

methylpyridinium chloride is stable on u.v. irradiation in neutral aqueous solution.[4]

We report a novel photohydration of pyridinium ions to *N*-alkylaminopentadienals *via* 1,2-dihydro-2-hydroxy-pyridines in alkaline solvents, comparing the results with those for formation of azabicyclo[3.1.0]hex-3-en-2-ols.

RESULTS AND DISCUSSION

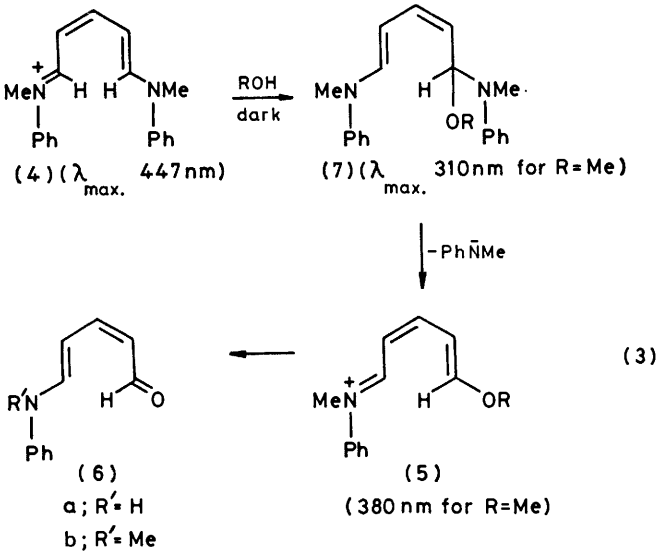
Photolysis of N-*Phenylpyridinium Chloride.*—Irradiation of *N*-phenylpyridinium chloride (1) (1.1×10^{-4}M) containing sodium methoxide (0.05M) in methanol afforded quantitatively a photoproduct (2) with a u.v. with electron-withdrawing groups CO_2H, CO_2Me, and peak at 313 nm (Figure 1). The spectral shift from 263 nm for (1) to 313 nm of (2) gives rise to isosbestic points



at 273 and 248 nm. Addition of excess of HCl to the reaction solution instantaneously converts (2) into 5-methoxypenta-2,4-dien-1-one anil (3). The structure of the anil (3) was confirmed by detection of aniline and glutaconaldehyde upon hydrolysis. But the intermediate could not be identified, though it is tentatively assigned as 1,2-dihydro-1-phenyl-2-methoxypyridine (2). All attempts to isolate (2) failed on account of its rapid collapse to the open-chain anil (3) on condensation.

Although the decomposition of (1) to (2) is complete within 2 min, control experiments occurred with difficulty, *e.g.*, 3 min irradiation gave <1% yield in aqueous methanol. In addition, no reaction occurred in the dark after standing for 60 min.

As reported by Zincke,[5] treatment of glutaconaldehyde bis-*N*-methylanil (4) with MeONa in methanol in the dark gave the methoxide adduct (7) with a u.v. maximum at 310 nm, followed by gradual degradation into the mono-*N*-methylanil (6b), *via* (5; R = Me). The u.v. peak of (5; R = Me) (380 nm) is close to that of (3) ($\lambda_{max.}$ 390 nm).



Photolysis of N-*Benzylpyridinium Chlorides.*—Irradiation of *N*-benzylpyridinium chloride (8a) (5×10^{-4}M) containing EtONa (0.2M) in EtOH afforded (9a) with a u.v. peak at 295 nm (Figure 2). Addition of excess of HCl instantaneously converts (8a) into 5-ethoxypenta-2,4-dien-1-one benzylimine (10a), which was confirmed by the detection of benzylamine and glutaconaldehyde upon hydrolysis [equation (4)].

In contrast to (1), no photoaddition of OMe^- to (8a) was observed. Neither EtO^- nor OH^- attacks (8a) in the dark. The monomethyl (8b and c) and dimethyl (8d and e) derivatives undergo a slower reaction, the yield depending on the position of the methyl groups (Table 1).

Photolysis of *N*-benzylpyridinium chloride (8a) (0.013M) in aqueous HCl (0.12M) yielded 2-benzylpyridine (*ca.* 4%) along with benzylamine (trace) [equation (5)].

Photolysis of N-*Methylpyridinium Chlorides.*—Irradiation of *N*-methylpyridinium chloride (11a) (5×10^{-4}M) containing EtONa (0.2M) in EtOH gave a photoproduct (12a) with u.v. peak at 290 nm. The spectral shift from 260 nm for (11a) to 290 nm for (12a) has an isosbestic point at 263 nm. Also acidification of mixture converts (12a) into (13a), which gave glutaconaldehyde on hydrolysis (h.l.p.c.).

Both mono- and di-methyl substituents retard the reaction remarkably as in the case of (8) as shown in Table 2. Aqueous alkaline (11a) did not give the corresponding 1,2-dihydro-adduct [ON^- instead of OEt^- in (12a)], upon photolysis, although (11a) disappeared efficiently. The photolysis of (11a) in aqueous NaOH or K_2CO_3 gave alternatively azabicyclo[3.1.0]hex-3-en-2-ol (14a) as reported by Kaplan *et al.*[1a] Mono-, di-methyl, and ethyl substituted azabicyclo[3.1.0]hex-3-en-2-ol were obtained from the corresponding pyridinium ions (11), some of them being new compounds.

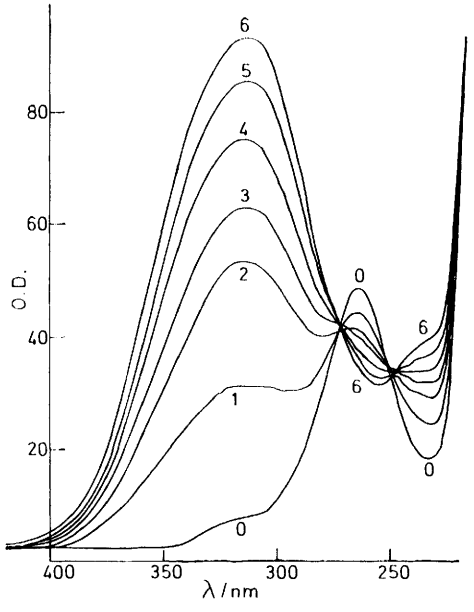


FIGURE 1 U.v. absorption of (1) (1.1×10^{-4}M) in an MeONa (0.05M) methanol solution: 0, before irradiation; 1—6, after consecutive 2 min irradiations

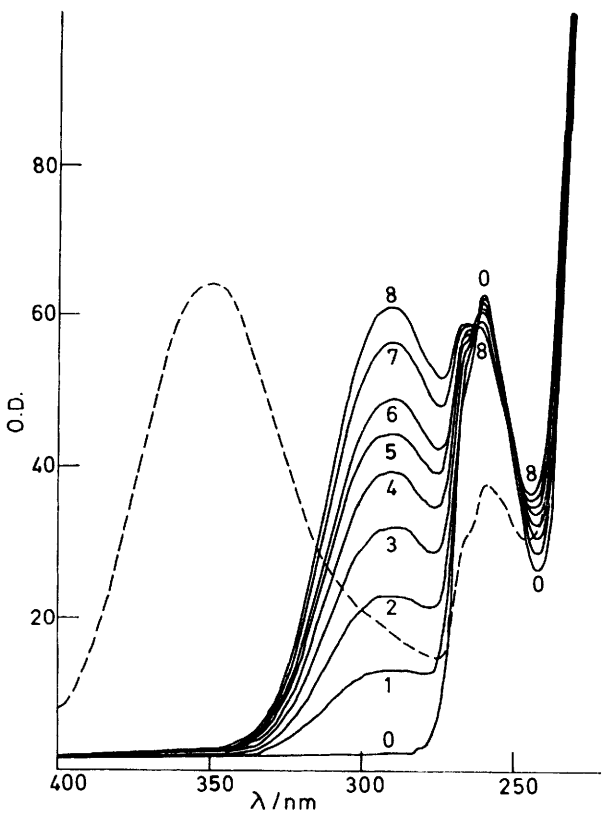


FIGURE 2 U.v. absorption of (11a) (5×10^{-4}M) in an EtONa (0.2M) ethanol solution: 0, before irradiation; 1—8, after consecutive 10 min irradiations. Dotted line (- - - -) indicates that after 10 min irradiation an excess of HCl was added

Table 3 indicates the photoreactivity of (11). The photoreactivity of (11) parallels in either aqueous AcOH or NaOH at least at an early stage, but the former photolysis was slowed down for (11c—e) probably because the products revert to the initial pyridinium ions as the solution becomes acidic.

In contrast to photolysis in alcoholic alkali, an ion with a methyl substituent in the ring tends to promote the reaction, an exception being the α-substituted ion which retards the reaction.

TABLE 1

Effect of methyl substituents on the formation of (9) upon photolysis of (8) in 0.2M-EtONa ethanol solution

Compound [a]	Relative yield of (a) [b]
(8a)	1
(8b)	0.18
(8c)	*c*
(8d)	0.11
(8e)	0.17

[a] All compounds (8) were irradiated for 45 s in 10 mm optical cells by a 300 W high pressure Hg lamp. [b] Compared with the value for unsubstituted (8a). [c] The 4-methyl isomer underwent a dark reaction with EtONa.

Although the photohydration products (14) steadily accumulate in aqueous NaOH, the photolysates (14) in aqueous AcOH disappear to form the original (11) or collapse to give (13). The products ratio (13) : (14)

(8)

a; $R^1 = R^2 = R^3 = H$
b; $R^1 = Me$, $R^2 = R^3 = H$
c; $R^1 = R^2 = H$, $R^3 = Me$
d; $R^1 = R^2 = Me$, $R^3 = H$
e; $R^1 = R^3 = Me$, $R^2 = H$

changes depending on the position of the methyl group in the starting (11), *i.e.* (11a and e—g) did not give (13) on photolysis in aqueous AcOH, but (11b—d) gave (13), whereas the 4-methyl isomer (11d) changes rapidly to (13) ($\lambda_{max.}$ 364 nm).

The photolysates in aqueous NaOH gradually reform (11) on standing in the dark after addition of excess of HCl. The yields of reformed (11) on the basis of photodecomposed (11) are as follows: 73% for (11a), 90% for (11b), 62% for (11c), 72% for (11d), 74% for (11e), and 82% for (11f).

Equal amounts of azabicyclo[3.1.0] isomers (14b and d)

TABLE 2

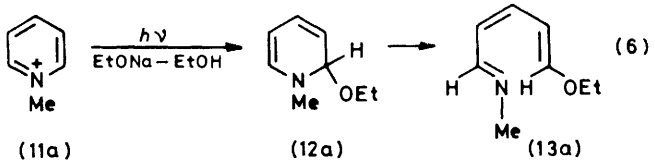
Effect of methyl substituents on the yield of (12) upon photolysis of (11) in 0.2M-EtONa ethanol solution

Compound [a]	Relative yield of (12) [b]
(11a)	1
(11b)	0.31
(11c)	0.15
(11d)	0.31
(11e)	0.13
(11f)	0.17
(11g)	0.17

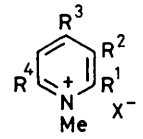
[a] All compounds (11) were irradiated in a 10 mm optical cell by a 300 W high pressure Hg lamp for 8 min. [b] Relative yields based on the value of unsubstituted (11a).

were formed from either (11b or c). Another isomer (14c) was obtained from (11d) along with (14b and d). A mixture of (14e and f) was obtained from (11e), and (14g) was formed from (11f), but the 2,6-dimethyl isomer (11g) yields no (14).

The independent decomposition of (14) indicates the rapid conversion of (14c) into (13d) with a rate constant of 5×10^{-2} min^{-1} even in neutral water. The other hydrated products (14a and e—g) yield no methyl imines (13). The effect of methyl substituent on the rate of decomposition (14) ⟶ (13) is as follows: (14c) ≫ (14b—d) > (14a, e—g). Therefore, pyridinium ions which can be photohydrated to give (14c) undergo



(11a) (12a) (13a) (6)



(11)

a; $R^1 = R^2 = R^3 = R^4 = H$, $X = ClO_4$
b; $R^1 = Me$, $R^2 = R^3 = R^4 = H$, $X = ClO_4$
c; $R^1 = H$, $R^2 = Me$, $R^3 = R^4 = H$, $X = I$
d; $R^1 = R^2 = H$, $R^3 = Me$, $R^4 = H$, $X = ClO_4$
e; $R^1 = R^2 = Me$, $R^3 = R^4 = H$, $X = ClO_4$
f; $R^1 = Me$, $R^2 = H$, $R^3 = Me$, $R^4 = H$, $X = I$
g; $R^1 = Me$, $R^2 = R^3 = R^4 = H$, $X = ClO_4$
h; $R^1 = H$, $R^2 = CONH_2$, $R^3 = R^4 = H$, $X = ClO_4$

directly the decomposition (11) ⟶ (13), but the other ions could not.

The failure of (11e) to give a parallel reaction is probably due to rapid reformation of (14e and/or f) to (11e). The photoreactivities of (11b and c) are quite

TABLE 3

Photolysis of some substituted pyridinium ions in 0.1M aqueous NaOH or 0.1M aqueous AcOH

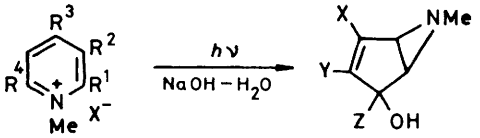
Pyridinium ions (11)	In 0.1M aqueous AcOH: Conversion of (11) (%)	In 0.1M aqueous AcOH: Relative yield	In 0.1M aqueous NaOH: Conversion of (11) (%)	In 0.1M aqueous NaOH: Relative yield
a	47.7	1	50.0	1
b	31.2	0.65	33.3	0.67
c	57.8	1.2	80.6	1.6
d	31.1	0.65	55.7	1.1
e	40.0	0.84	72.0	1.4
f	42.6	0.89	43.6	0.87
g	4.5	0.09	0	0

[a] Irradiated by a 300 W high pressure Hg lamp in a 10 mm optical cell for 3 min.

different, although they afford the same products (14b and d).

As reported by Kaplan,[1a] the products may be formed by hydration of cation (16), but preliminary 1,2-shifts of nitrogen may occur *via* (15) [equation (8)].

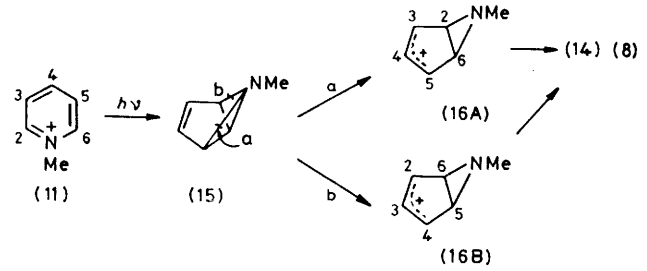
The difference of photoreactivity between (11b) and



(11) (14) (7)

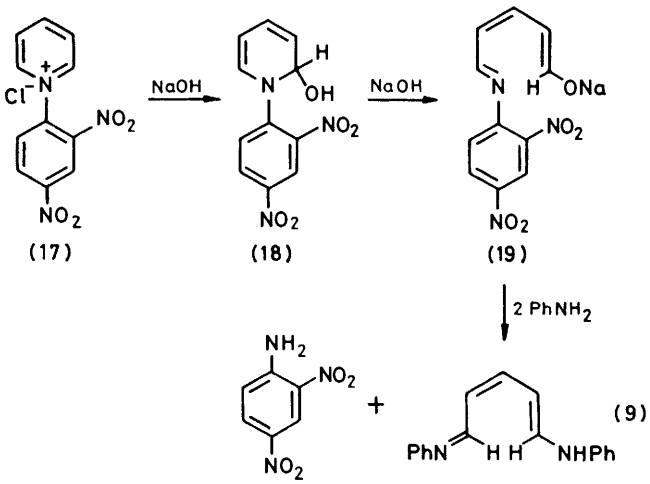
a; X = Y = Z = H
b; X = Y = H, Z = Me
c; X = Z = H, Y = Me
d; X = Me, Y = Z = H
e; X = H, Y = Z = Me
f; X = Y = Me, Z = H
g; X = Z = Me, Y = H
h; X = Y = H, Z = Et
i; X = Et, Y = Z = H

(11c) can be explained similarly. The lower reactivity of (11b) is attributable to the 1,2-shift of nitrogen in contrast to the direct photolysis of (11c) to (14).

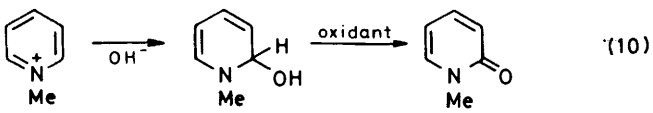


Criterion for Different Pathways.—Both in neutral and basic solutions, *N*-methylpyridinium ions (11) are gradually photolysed to (14), while *N*-phenyl- and *N*-benzylpyridinium ions (1) and (8) afford no analogues of (14). An n.m.r. study shows that in photolysis of (11) in alkaline D_2O the signals at δ 5—6 assigned to vinyl protons of (14) gradually appeared and increased on u.v. irradiation, whereas (1) and (8) showed no n.m.r. change.

The characteristic stability of the pyridine ring is lost in Type A reactions of quaternary pyridinium ions in the dark. 1-(2,4-Dinitrophenyl)pyridinium chloride (17) is a typical case. In aqueous NaOH in the dark, (17) forms (19) by ring rupture *via* (18), which on treat-



ment with aniline gives glutaconaldehyde dianil and 2,4-dinitroaniline [equation (9)]. A similar nucleophilic attack of hydroxide ion on some pyridinium ions was reported for alkaline oxidation to *N*-methyl-2-pyridone [equation (10)].[6]



Unfortunately, there is no report on the isolation of 2-hydroxy-1,2-dihydropyridines, but nucleophilic attack by halide or cyanide is observed.[7,8] As for (17), photostimulated hydration of pyridinium ions was observed, which gave 2-alkoxy(hydroxy)-1,2-dihydropyridines.

The differences of reactivity towards hydration may be due to the nucleophilicities of the attacking alkoxide anions, which are parallel to their basicities: $HO^- < MeO^- < EtO^- < Bu^tO^-$. In fact, an attack of HO^- to the pyridinium ions occurs in DMSO in the dark, but not in water or methanol.[9]

Nucleophilic addition to *N*-pyridinium ion may be affected by u.v. excitation of the ion, and this is promoted by increasing acidity of the ions. Although no data are available on the pK_a values of an electronically excited pyridinium ion, it is apparent that the pK_a is lowered by photoexcitation.

EXPERIMENTAL

All m.p.s were measured on a hot plate by a Yanagimoto micro apparatus. N.m.r. spectra were recorded on a Hitachi instrument, model R-24B, and u.v. spectra by a Hitachi spectrophotometer, model 124. G.l.c. analysis was done by a Yanagimoto gas chromatograph, model G 180, with a flame ionisation detector employing PEG 20M on Chamelite CS (1.7 m × 4 mm) and/or polyethyleneimine on Chromosorb W (1 m × 4 mm). High pressure liquid chromatography was done by a Yanagimoto liquid chromatograph, model L-1030, with a u.v. (254 nm) detector employing a Yanapak DMS column using a mixture of methanol and water as eluant.

Materials.—Quaternary pyridinium salts were synthesised by the reaction of the appropriate pyridines with either alkyl halides or dimethyl sulphate followed by treatment with saturated sodium perchlorate. M.p.s after recrystallisation from acetone and/or ethanol were as follows: (8b) chloride, 143 °C; (8c) chloride, 186—187 °C; (8d) chloride, 147—148.5 °C; (8e) chloride, 167—168.5 °C; (11a) perchlorate, 90—92 °C; (11b) perchlorate, 124—125.5 °C; (11c) iodide, 96—97 °C; (11d) perchlorate, 88—90 °C; (11e) perchlorate, 129—131 °C; (11f) iodide, 121.5—122 °C; (11g) perchlorate, 196—197 °C. The n.m.r. spectra were all in accord with the structures. *N*-Phenylpyridinium chloride (1) was obtained from *N*-(2,4-dinitrophenyl)pyridinium chloride by a known procedure, m.p. 100—102 °C, $\lambda_{max.}$ 263 nm (ε 8 150).[10]

Photolysis of N-*Phenylpyridinium Chloride* (1) *in* MeOH *with* MeONa.—A methanol solution of *N*-phenylpyridinium chloride (1) (1.1×10^{-4}M) containing 0.05M-MeONa was irradiated by a 300 W high pressure Hg lamp (Halos HIP 300) in a 10 mm optical quartz cell. The u.v. peak at 263 nm was shifted to 313 nm. The reaction was complete within 2 min. The product gradually decomposed to 5-methoxypenta-2,4-dien-1-one anil (3) either on standing in the dark or by addition of excess HCl or AcOH. The anil (3) was converted to aniline and glutaconaldehyde. Aniline was detected by h.l.p.c. equipped with a Yanapak DMS column using 70% aqueous MeOH as eluant (50 kg cm^{-2}, R_t 3.4 min detected as $PhNH_2$). Glutaconaldehyde was detected by u.v. comparison with an authentic specimen ($\lambda_{max.}$ 306 nm).[4]

Photolysis of N-*Benzylpyridinium Chloride* (8a) *in Alkaline* EtOH.—*N*-Benzylpyridinium chloride (8a) (5×10^{-4}M) in EtOH containing EtONa (0.2M) was irradiated by a 300 W high pressure Hg lamp (Halos HIP 300) in a 10 mm quartz cell. The u.v. peak shifted from 257 to 295 nm. Addition of excess HCl to the product gave 5-ethoxypenta-2,4-dien-1-one benzylimine (10a) quantitatively. The imine (10a) was further hydrolysed to give glutaconaldehyde and benz-

ylamine which were characterised by h.l.p.c. (50 kg cm^{-2}; 70% aqueous MeOH, Yanapak DMS, R_t 2.2 min detected as $PhCH_2NH_2$,HCl).

Photolysis of N-Benzylpyridinium Chloride (8a) *in Aqueous* HCl.—An aqueous solution (500 ml) of *N*-benzylpyridinium chloride (1.3 g, 0.013M) containing HCl (0.12M) was irradiated by a 30 W low pressure Hg lamp (HIL 30) for 26 h. The mixture, after neutralisation with K_2CO_3 followed by condensation *in vacuo*, was chromatographed on alumina to give 2-benzylpyridine (46 mg, 4%) and benzylamine (trace). The products were characterised by g.l.c. comparison with authentic samples on a column of polyethyleneimine containing KOH.

Photolysis of N-Benzylpyridinium Chloride (8a) *in Alkaline Water.*—A deuterium oxide solution (0.7 ml) of (8a) (66.5 mg) containing K_2CO_3 was irradiated in a quartz n.m.r. tube. The ion (8a) was gradually consumed on u.v. irradiation, accompanied by an increase of the benzylamine n.m.r. signal at δ 3.5. No signal for the vinyl and aziridine ring protons of azabicyclo[3.1.0]hexene was observed.

Photolysis of N-Methylpyridinium Perchlorate (11a) *in Alkaline* MeOH.—*N*-Methylpyridinium perchlorate (11a) (1.7 g) in MeOH (500 ml) containing KOH was irradiated by a 300 W high pressure Hg lamp for 4 h to decompose 80% of the starting (11a). Alumina chromatography (Merck; activity II—III) of the condensed mixture eluted a yellow oil (*ca.* 120 mg, 11%) using benzene as eluant. The oil was characterised as 4-methoxy-6-azabicyclo[3.1.0]hex-2-ene (14a; 4-OMe for 4-OH), δ(CCl_4) 2.22 (3 H, s, N-Me), 2.3 (2 H, m, 1-,5-H), 3.29 (3 H, s, OMe), 4.00br (1 H, s, MeOCH), 5.75 (1 H, d, vinyl H), and 6.15 (1 H, d, vinyl H).

Photolysis of N-Methylpyridinium Perchlorate (11a) *in Alkaline Water in an N.m.r. Tube.*—A deuterium oxide solution (0.7 ml) of (11a) (72.2 mg) containing K_2CO_3 (64 mg) was irradiated in a quartz n.m.r. tube. The signals for (11a) disappeared gradually with simultaneous increase of the signals [δ 6.6 (*J* 6 Hz), 5.87 (*J* 6 Hz), 2.3, 2.6, and 2.74] for (14a).

Photolysis of Methyl-substituted N-Methylpyridinium Ions (11b—g).—Methyl-substituted *N*-methylpyridinium ions (0.8—1.0 g) in methanol (500 ml) containing K_2CO_3 or KOH were irradiated until the starting material had almost disappeared. The mixtures were condensed *in vacuo* and then purified by Al_2O_3 (Merck; activity II—III) chromatography to give the azabicyclo[3.1.0] isomers. The data were as follows: pyridinium ion photolysed (11), azabicyclo[3.1.0]isomers (14) formed, g.l.c. retention times using polyethyleneimine (20%) on Chromosorb W containing KOH (relative to aniline), methyl chemical shifts: (11a), (14a), 1.29; (11b) (2-Me), (14b and d), 0.83 and 1.28, respectively; (11b) (2-Et), (14h and i), 0.94 and 1.37, respectively; (11c) (3-Me), (14b and d), 0.83 and 1.28, respectively; (11d) (4-Me), (14b, d, and c), 0.83, 1.28, and 1.36, respectively; (11c) (2,3-Me_2), (14e and f), 0.95 and 1.00, respectively; (11f) (2,4-Me_2), (14g), 0.85.

[8/1551 *Received, 24th August,* 1978]

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