s, OCH_3), 128.7 (J = 7.7 Hz, C-7), 132.8 (J = 18.7 Hz, C-6 or C-8), 135.2 (J = 11.0 Hz, C-6 or C-8), 140.2 (J = 20.0 Hz, C-5), 164.0 (J = 2.2 Hz, C=O), 165.2 (J = 3.3 Hz, C=O); ^1H NMR ($CDCl_3$, 300 MHz) δ 1.65 (d, $^2J_{PH}$ = 15.2 Hz, PCH_3), 1.55–1.85 (m, 2 H, CH_2), 3.79 and 3.82 (both s, OCH_3), 4.22 (d of m, $^3J_{PH}$ = 38 Hz, H-1), 4.43 (m, H-4), 6.33 (m, 2 H, olefinic H).

Anal. Calcd for $C_{12}H_{15}O_5P$: C, 53.34; H, 5.60; P, 11.46. Found: C, 53.44; H, 5.77; P, 11.61.

2-Phenyl-2-phosphabicyclo[2.2.2]octa-5,7-diene 2-Oxide (15). To 0.229 g (0.747 mmol) of **13** in 8 mL of dry pyridine was added 1.33 g (2.99 mmol) of lead tetraacetate. The mixture was placed in an oil bath at 75 °C until carbon dioxide evolution ceased. The solution was rotary evaporated and chromatographed on alumina with 0% MeOH in $CHCl_3$ and then on silica gel with 3% MeOH in $CHCl_3$, yielding 0.0645 g (40%) of **15**: ^{31}P NMR ($CDCl_3$) δ +40.5; ^{13}C NMR ($CDCl_3$) δ 25.8 (J = 108.8 Hz, C-3), 35.7 (J = 9.9 Hz, C-4), 43.0 (J = 52.7 Hz, C-1), 128.2 (J = 11.0 Hz, C-meta), 129.1 (J = 8.8 Hz, C-6 or C-7), 129.2 (J = 4.4, C-6 or C-7), 131.6 (J = 3.3 Hz, C-para), 131.7 (J = 8.8 Hz, C-ortho), 132.5 (J = 94.5 Hz, C-ipso), 134.8 (J = 22.0 Hz, C-5 or C-8), 135.9 (J = 19.8 Hz, C-5 or C-8); ^1H NMR ($CDCl_3$, 300 MHz) δ 1.70 (m, 1 H, unresolved d of t, C*H*H), 2.0 (m, 1 H, unresolved d of d, CH*H*), 4.10 (m, 2 H, H-1 and H-4), 6.18 (m, 1 H, olefinic H), 6.45 (m, 1 H, olefinic H), 6.65 (m, 2 H, olefinic H), 7.3–7.9 (Ar H); MS, m/z 216.0702 (M^+, $C_{13}H_{13}OP$; calcd 216.0704).

Dimethyl 2-*syn*-Phenyl-2-phosphabicyclo[2.2.2]oct-5-ene-7,8-dicarboxylate (16). To a solution of 0.559 g (0.0041 mol) of trichlorosilane in 50 mL of dry benzene was added 0.9775 g (0.0123 mol) of dry pyridine in 10 mL of dry benzene. A solution of 0.25 g (0.00 75 mol) of **12** in 5 mL of dry benzene was added. The mixture was refluxed for 1.5 h and then chilled in an ice bath for addition of 15 mL of 30% NaOH. The mixture was stirred for 15 min, and the layers were separated. The H_2O layer was washed with benzene (2 × 10 mL). The combined benzene layers were dried ($MgSO_4$) and rotary evaporated to yield 0.23 g (96.4%) of **16** as a clear oil: ^1H NMR ($CDCl_3$) δ 1.5–3.7 (m, 12 H, sp^3 CH), 5.9–6.5 (m, 2 H, =CH), 7.1–7.5 (m, C_6H_5); ^{13}C NMR, Table III; ^{31}P NMR ($CDCl_3$) δ –40.0.

To a sample of **16** in benzene was added excess methyl iodide. The mixture was stirred in the absence of light for 24 h at room temperature. Rotary evaporation gave a white solid that was recrystallized from methanol/ethyl acetate: mp 208–209 °C dec; ^{31}P NMR (DMSO-d_6) δ +24.9; ^{13}C NMR (partial, DMSO-d_6) δ 7.04 (J = 46.4 Hz, PCH_3), 29.0 (J = 48.8 Hz, C-1 or C-5), 32.1 (J = 8.6 Hz, C-4), 45.8 (J = 8.6 Hz, C-5 or C-6), 52.1 and 52.3 (both s, OCH_3), 170.2 (s, C-9), 171.3 (J = 10.8 Hz, C-10).

Anal. Calcd for $C_{18}H_{22}IO_4P$: C, 46.97; H, 4.82; P, 6.73. Found: C, 46.68; H, 5.19; P, 6.83.

Dimethyl 2-Methyl-2-phosphabicyclo[2.2.2]octa-5,7-diene-5,6-dicarboxylate (18). A solution of 0.400 g (0.001 48 mol) of **14** in 16 mL of benzene and 2 mL of toluene was stirred with 2.15 g (0.0158 mol) of trichlorosilane at 0 °C for 4.5 h. The solution was evaporated to give a clear oil, which was dissolved in 80 mL of dichloromethane and then neutralized with 1 mL of 30% KOH. The organic layer was dried over molecular sieves and after solvent removal left **18** as a pale yellow oil (0.34 g, 90%): ^{31}P NMR ($CDCl_3$) δ –36.0; ^1H and ^{13}C NMR, Table IV.

The phosphine was quaternized with methyl iodide to give the methiodide **19**: mp 163–164 °C; ^{31}P NMR ($CDCl_3$) δ +31.6; ^1H and ^{13}C NMR, Table IV.

Anal. Calcd for $C_{13}H_{18}IO_4P$: C, 39.41; H, 4.58. Found: C, 39.00; H, 4.25.

2-Phenyl-2-phosphabicyclo[2.2.2]octa-5,7-diene (20). To 0.22 g (0.001 02 mol) of **15** in 15 mL of dichloromethane was added 2.0 g (0.0147 mol) of trichlorosilane. The mixture was stirred at –6 to –8 °C for 4.5 h and then worked up as for **18**. The major product in the residual oil was phosphine **20** [^{31}P NMR ($CDCl_3$) δ –29.0] with 8% unreacted **15** and 5% of a secondary phosphine [^{31}P NMR ($CDCl_3$) δ –71 ($^1J_{PH}$ = 200 Hz) (possibly PhMePH, δ –72.3 (^1J = 222 Hz[28]))]. The phosphine was used in this condition for ^1H and ^{13}C NMR (Table III).

Phosphine **20** was converted to the crystalline methiodide **21** by stirring with methyl iodide in benzene; **21** was recrystallized from acetone and had mp 160–163 °C: ^{31}P NMR ($CDCl_3$) δ +23.4; ^1H and ^{13}C NMR, Table III.

Anal. Calcd for $C_{14}H_{16}IP$: C, 49.14; H, 4.71. Found: C, 48.69; H, 4.51.

Acknowledgment. This work was supported by a grant from the U.S. Army Research Office. A.N.H. thanks Lakehead University for a sabbatical leave of absence.

Registry No. **3**, 96991-69-4; **4a**, 113403-82-0; **4b**, 113403-80-8; **5**, 113403-83-1; **6**, 96991-68-3; **7a**, 113403-84-2; **7b**, 113403-81-9; **8**, 113403-85-3; **9**, 113403-86-4; **10**, 113403-87-5; **11**, 113403-88-6; **12**, 113403-89-7; **13**, 113403-90-0; **14**, 113403-91-1; **15**, 113403-92-2; **16**, 113403-93-3; **16** (methiodide), 113403-98-8; **18**, 113403-94-4; **19**, 113403-95-5; **20**, 113403-96-6; **21**, 113403-97-7; maleic anhydride, 108-31-6; *N*-phenylmaleimide, 941-69-5; dimethyl acetylenedicarboxylate, 762-42-5; trichlorosilane, 10025-78-2.

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Steric Effects on Rates and Equilibria of a Cation–Anion Combination Reaction: The Methoxide Attachment to 4-Substituted 2,6-Di-*tert*-butylpyrylium Cations

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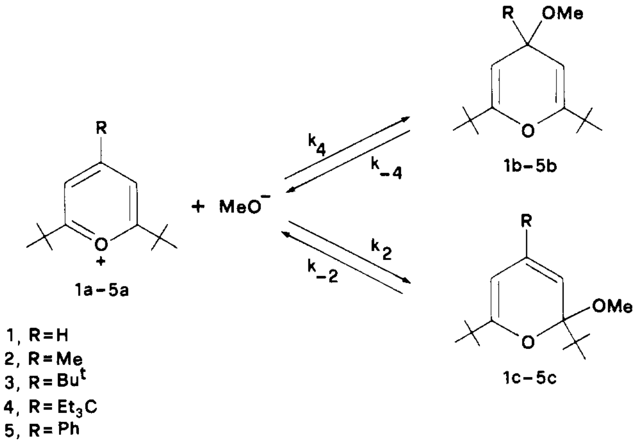
Received June 1, 1987

The kinetic and equilibrium constants for the reaction of 2,6-di-*tert*-butyl-4-R-pyrylium cations (R = H, Me, *t*-Bu, Et_3C, Ph) with methoxide ion, to yield the corresponding 2*H* and 4*H* adducts, have been determined in MeOH at 25 °C. The reaction involves the kinetically controlled formation of the 4*H* adduct only when R = H or Me, whereas in the other cases a mixture of both the 2*H* and 4*H* adducts is formed. The 2*H* adducts are the thermodynamically favored products, though in the case of the methyl-substituted cation a comparable amount of the anhydro base is also formed. The rate constants for the formation of the 4*H* adducts follow a regular trend showing a low sensitivity to steric effects, whereas the corresponding equilibrium constants are not affected by steric interactions until a certain value of the steric hindrance of the γ-substituent is reached. Above this value steric effects are greater on equilibria than on rates. These observations are interpreted in terms of an ion pair-like transition state in which the nucleophile specifically interacts with the electrophilic center.

Nucleophile–cation combination reactions play a central role in physical organic chemistry, due in part to the extensive work carried out by Ritchie,[1] which established a new empirical nucleophilicity scale to correlate the re-

Scheme I



activity of preformed organic cations by a single parameter equation (eq 1).

$$\log k = \log k_0 + N_+ \qquad (1)$$

In spite of the large body of data that follows eq 1 there are also frequent deviations, a large part of which has been ascribed to steric effects.[1c] Nevertheless not even a single quantitative evaluation of the importance of steric effects on cation–anion combination reactions has appeared to date in the literature.

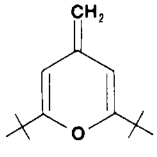
In previous work we have shown that pyrylium[2] and thiopyrylium[3] cations, owing to their ambident character (provided that α positions are symmetrically substituted), can provide useful information about the mechanistic details of cation–anion combination reactions.

With the aim to gain an understanding of the role of steric factors in this class of reactions, we have undertaken a kinetic and thermodynamic study of the reaction of 2,6-di-*tert*-butyl-4-R-pyrylium cations **1a**–**4a** with methoxide ion, in methanol, at 25 °C, to give the corresponding adducts, namely, the 4*H*-pyrans **1b**–**4b** and the 2*H*-pyrans **1c**–**4c**, according to Scheme I. The cation **5a**, whose reaction with methoxide ion has been previously studied,[2] completes the series.

Results

The kinetic and thermodynamic investigation of the methoxide attachment to the cations **1a**, **3a**, and **4a** relies on a previous ^{1}H NMR study of the reactions carried out at low (−40 °C) and at room (25 °C) temperature.[4] The ^{1}H NMR study has been here extended to the cation **2a**.

At low temperature, the methoxide attachment to the cations **1a**–**4a** is subjected to kinetic control. Under this condition the cations **1a** and **2a** show only the formation of the 4*H*-pyrans **1b** and **2b**, respectively, whereas the cations **3a** and **4a** yield both the adducts with molar ratios 4*H*/2*H* equal to 0.44 and 0.11, respectively. When the reaction mixtures are allowed to equilibrate at 25 °C, the cations **1a**, **3a**, and **4a** yield exclusively the corresponding 2*H*-pyrans, whereas the cation **2a** yields a mixture of the 2*H* adduct **2c** and of the corresponding anhydro base **2d** with a molar ratio **2c**/**2d** = 0.7.



2d

The kinetic experiments were carried out in methanol at 25.0 °C, under pseudo-first-order conditions, by mixing the substrates with a large excess of sodium methoxide or Et_3N/Et_3NH^+ buffers depending on the reactivity of the substrate. In all the kinetic experiments carried out with Et_3N/Et_3NH^+ buffers we had no evidence of general acid–base buffer catalysis. Upon mixing all the substrates showed a fast process that, in accordance with the NMR observations, led to their complete disappearance. Taking into account the NMR patterns obtained under the kinetically controlled conditions, the relaxation time[5] of this process τ_1 can be related to the formation of the adducts, according to eq 2 for the cations **1a** and **2a** and to eq 3 for the cations **3a** and **4a**.

$$1/\tau_1 = k_4[\mathrm{MeO^-}] \qquad (2)$$

$$1/\tau_1 = (k_2 + k_4)[\mathrm{MeO^-}] \qquad (3)$$

A slower process widely separated from the first one and independent of [MeO$^-$] is observed for the cations **1a**, **3a**, and **4a**. This process, whose relaxation time we indicate with τ_2, involves the conversion of the 4*H* adduct into the thermodynamically more stable 2*H* one. This process occurs through the intermediacy of the substrate, which is present in steady-state concentration. Therefore the application of the steady state approximation affords eq 4 for the cation **1a** and eq 5 for the cations **3a** and **4a**.

$$1/\tau_2 = k_2k_{-4}/k_4 \qquad (4)$$

$$1/\tau_2 = k_2k_{-4}/(k_2 + k_4) \qquad (5)$$

Note that eq 3 and 5 reduce to eq 2 and 4, respectively, when $k_4 \gg k_2$. In the case of the cation **2a** the equilibration process of the 4*H*-pyran **2b** into the corresponding 2*H* isomer **2c** is complicated by the concurring deprotonation of the substrate leading to the anhydro base **2d**. Owing to the complications involved we did not investigate this equilibration process any further.

The kinetic and equilibrium constants have been evaluated as follows.

Cation 1a. According to eq 2, a plot of $1/\tau_1$ vs [MeO$^-$] afforded k_4. The equilibrium constant K_4 ($=k_4/k_{-4}$) could be obtained by stopped-flow absorbance measurements with proper buffer solutions (see Experimental Section). The kinetic constant k_2 was obtained, according to eq 4, multiplying $1/\tau_2$ by K_4. The equilibrium constant K_2 ($=k_2/k_{-2}$) was obtained spectrophotometrically using appropriate buffer solutions (see Experimental Section).

Cation 2a. The constants k_4 and K_4 were evaluated as for the cation **1a**. The other kinetic and equilibrium constants were not evaluated.

Cations 3a and 4a. According to eq 3, a plot of $1/\tau_1$ vs [MeO$_-$] afforded the term $k_2 + k_4$. Since at the end of the first process the substrate is completely converted into the 4*H* and 2*H* adducts, the ratio of their concentrations ($[4H]_1/[2H]_1$) coincides with the k_4/k_2 term. Considering that at the end of the reaction the concentration of 2*H* adduct ($[2H]_2$) coincides with $[2H]_1 + [4H]_1$, the relationship 6 is obtained.

$$\frac{k_4}{k_2} = \frac{[2H]_2 - [2H]_1}{[2H]_1} \qquad (6)$$

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(5) The relaxation time is the inverse of the observed pseudo-first-order kinetic constant of the process: Bernasconi, C. F. *Relaxation Kinetics*; Academic: New York, 1976.

Table I. Rate and Equilibrium Constants for the Reactions of Cations 1a–5a with Methoxide Ion in MeOH at 25 °C

cation	k_4, s^{-1} M^{-1}	k_{-4}, s^{-1}	K_4, M^{-1}	k_2,[a] s^{-1} M^{-1}	k_{-2}, s^{-1}	K_2,[a] M^{-1}
1a	1.9×10^8	5.6×10^{-2}	3.5×10^9	4.3×10^6	3.9×10^{-6}	1.1×10^{12}
2a	1.9×10^7	1.8	1.0×10^7			
3a	2.7×10^5	6.0×10^{-2}	4.5×10^6	6.1×10^5	1.0×10^{-4}	5.9×10^9
4a	5.8×10^4	1.3×10^{-1}	4.6×10^5	3.9×10^5	2.9×10^{-5}	1.3×10^{10}
5a[b]	$1.3_5 \times 10^6$	2.7	5.1×10^5	3.5×10^5	2.9×10^{-5}	1.2×10^{10}

[a] Uncorrected for the statistical factor. [b] From ref 2.

Therefore absorbance measurements carried out at a wavelength where only the $2H$ adduct absorbs, at the end of the first and the second process, respectively, allowed the evaluation of k_4/k_2 by eq 6. The k_4/k_2 values so obtained for the cations **3a** and **4a**, 0.44 and 0.15, respectively, are in good accordance with the $4H/2H$ ratios obtained at −40 °C by ^{1}H NNR, thus indicating a negligible effect of the temperature on the rate ratios. From the terms $k_4 + k_2$ and k_4/k_2 the inidividual kinetic constants k_2 and k_4 were evaluated. The constant k_{-4} could be evaluated from eq 5, whereas the equilibrium constant K_2 was obtained with the same technique used for the cation **1a**.

The kinetic and equilibrium constants for the reaction of cations **1a–4a**, together with the corresponding data for the cation **5a** are reported in Table I. Kinetic and equilibrium constants not explicitily indicated in the test were calculated by the relationships $K_4 = k_4/k_{-4}$ and $K_2 = k_2/k_{-2}$.

Discussion

Our analysis of steric and electronic effect on equilibria is in terms of ipso substituent effects. The ipso effect can be defined as follows: given a R-substituted aromatic compound undergoing attack at ipso position by a reagent X, the ipso effect is a measure of the interactions, in free energy terms, between the geminal X and R groups, referred to the case in which R = H.

In a previous work[6] we proposed to measure ipso effects, in the case of charged aromatic substrates such as pyrylium and thiopyrylium ions, by eq 7, where $(K_4/K_2)_R$ refers to

$$\Delta\Delta G^{\ominus} = -RT \ln \frac{(K_4/K_2)_R}{(K_4/K_2)_H} \qquad (7)$$

a cation bearing a R substituent in γ-position and $(K_4/K_2)_H$ to the corresponding cation with R = H. Equation 7 is a valid measure of ipso effects if the free energy of the $2H$ adduct is negligibly affected by the electronic effect of the R substituent.

The equilibrium data reported in Table I allow the evaluation of ipso effects for the groups *t*-Bu (0.8 kcal/mol), Ph (2.6 kcal/mol), and Et$_3$C (2.7 kcal/mol). If one assumes that the equilibrium constant K_2 for the cation **2a** is similar to that of the cation **3a**, it is possible to estimate the ipso effect also for the group Me (~0.4 kcal/mol).

Previous results[6] based on 2,6-diphenyl-4-R-thiopyrylium cations allowed the evaluation of ipso effects for *t*-Bu (0.3 kcal/mol), Ph (2.4 kcal/mol), and OMe (−3.0 kcal/mol). The accordance of the two estimations for *t*-Bu and Ph is good if one considers that these were based on completely different systems.

The ipso effect of Me and *t*-Bu groups is very low, thus indicating negligible steric and electronic interactions between these groups and the geminally linked OMe group in the $4H$ adducts **2b** and **3b**. On the contrary steric interactions are clearly significant in the case of the bulky Et$_3$C group. While the stabilizing ipso effect of *gem*-dimethoxy groups is well recognized and ascribed to a negative type of hyperconjugation,[7] the destabilizing effect of the geminally linked Ph and OMe groups is without precedents. One might suspect that, in this case, the assumption on which eq 7 is based no longer holds. However this seems unlikely because, judging from the equilibrium constants K_2 phenyl and alkyl groups behave similarly, thus ruling out any peculiar electronic effect of the phenyl group on both the cation and the $2H$ adduct. The destabilizing ipso effect of the phenyl group could hardly be attributed to steric interactions, since these are negligible in the presumably more crowded $4H$-pyran **3b**. At present we cannot offer convincing explanations about the origin of such effect, and we limit ourselves to record the experimental data. However, we believe that electronic interactions should be held responsible for it.

As far the rate data are concerned, it is apparent that the substituents in the γ-position stabilize the positive charge on the cation with respect to hydrogen by nearly the same amount, thus yielding very similar values of the k_2 constants. On the contrary the k_4 constants, spanning more than 3 powers of 10, are principally affected by steric effects. Owing to the limited number of experimental data available, the application of the classical Taft's treatment for the separation of polar and steric factors by the two parameter eq 8 would be without much physical meaning.[8]

$$\log k/k_0 = \rho^*\sigma^* + \delta E_s \qquad (8)$$

We feel that a direct comparison between the k_4 values and the rate constants for the base-catalyzed hydrolysis of esters having the corresponding substituents in the acyl component should be of greater significance. These values relative to that of the Me group have been reported by Taft[9] for H, *t*-Bu, and Ph ($\log (k/k_0)_B$ = 2.46, −2.38, −1.06, respectively). Although the datum for the group Et$_3$C is not available, it can be estimated on the basis of the equation defining the polar substituent constant σ^*,[8] which rearranged gives eq 9.

$$\log (k/k_0)_B = 2.48\sigma^* + E_s \qquad (9)$$

However, there is some uncertainty on the most appropriate σ^* and E_s values to be attached to the Et$_3$C group. The E_s value reported by Taft (−3.8)[8] has been criticized by Dubois et al.[10] who put forward a revised Taft scale (E_s'), according to which a significantly more negative value (−5.29) should be assigned to this group. The σ^* value for Et$_3$C can be estimated on the basis of the simple additivity rule of inductive effects,[8] i.e., by eq 10 or 11.

$$\sigma^*_{\mathrm{Et_3C}} = 3\sigma^*_{\mathrm{CH_2Et}} \qquad (10)$$

$$\sigma^*_{\mathrm{Et_3C}} = \sigma^*_{\mathrm{CHEt_2}} + \sigma^*_{\mathrm{CH_2Et}} \qquad (11)$$

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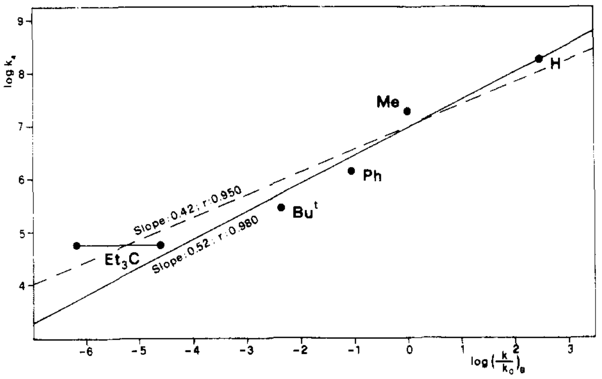


Figure 1. Plot of log k_4 against log $(k/k_0)_B$. The solid and dashed regression lines refer to the two extreme values for Et_3C (−4.64 and −6.19, respectively).

The two equations give the consistent values of −0.345 and −0.340, respectively. However two recently proposed[11] mathematical expressions yield slightly more negative values (−0.362 and −0.361, respectively). Taking into account these results the value of log $(k/k_0)_B$ for Et_3C should lie between the two extreme values of −4.64 and −6.19.

Figure 1 shows the plot of log k_4 vs log $(k/k_0)_B$. Two regression lines are considered which respectively take into account the two extreme values for Et_3C. The best of the two correlations (slope = 0.52; r = 0.980) refers to the "classical" value for Et_3C, i.e., that based on Taft's E_s constant and on the additivity rule of polar effects.

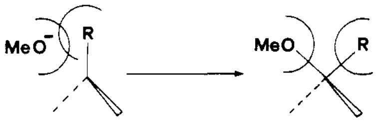
The existence of a satisfactory correlation between the methoxide attachment to pyrylium cations and the base-catalyzed hydrolysis of esters indicates that the rates of the two reactions are affected by the same relative contribution of steric and electronic effects. This is not unreasonable because in both cases a nucleophilic attachment on a trigonal carbon atom occurs.

Since the base-catalyzed ester hydrolysis is related to σ^* and E_s constants by eq 9, the sensitivity δ of the pyrylium reaction to the steric parameter E_s coincides with the slope of the plot in Figure 1, whereas the sensitivity ρ^* to the polar constant σ^* is 2.48 times this slope (ρ^* = 1.0–1.3). The factor 2.48 has been included in the Taft's treatment to make the σ^* scale as much like the Hammett σ scale as possible;[8] therefore the ρ^* value should be comparable with the ρ value referring to the methoxide attachment to the γ-position of 2,6-di-*tert*-butyl-4-phenyl-substituted pyrylium cations, as indeed it is the case, being ρ = 1.2.[2]

Apart the uncertainty on the precise value of the slope, the pyrylium reaction shows a remarkable low sensitivity to steric effects. This feature is probably common to the large majority of cation–anion combination reactions and would explain why the N_+ scale is so successful in correlating the rates of combination reactions with largely different steric requirements.[1c]

It is instructive to speculate about the relative importance of steric interactions in the 4*H* adducts and in the corresponding transition states. Apart the 4*H* adduct **5b**, which according to our analysis on ipso effects suffers from a specific electronic destabilization that precludes the analysis of steric factors, ipso steric interactions are practically negligible in the adducts **2b** and **3b**, whereas they are significant in the more crowded adduct **4b**. The transition states leading to the formation of the adducts **2b** and **3b** seem to be significantly more crowded than the corresponding final products. Indeed while there is a drop of a factor 70 in the k_4 value on going from Me to *t*-Bu, the corresponding equilibrium constant K_4 only changes by about a factor 2. This is one of the few remarkable cases in which structural variations cause larger effects on rates than on equilibria. We suggest that the greater crowding of the transition state can be ascribed to a nearly sp^2 hybridization of the C-4 atom, as depicted in Scheme II. A tight ion pair-like transition state in which the nucleophile specifically interacts with the electrophilic carbon appears from this description, and indeed such hypothesis has already been suggested for this class of reactions on different grounds.[3,4,12]

Scheme II



It should be remarked that the steric course depicted in Scheme II is in contrast with common beliefs based on steric effects in S_N1 reactions. In fact it is commonly accepted that during unimolecular conversion of an sp^3-hybridized ground state to an intermediate with sp^2 hybridization, the system may undergo a reduction in strain due in part to a decrease of the interaction between the leaving group and the rest of the molecule (*F* strain).[13] However we believe that *F* strain is important only in overcrowded molecules, and indeed it is apparent that on going from *t*-Bu to Et_3C slightly larger steric interactions are produced in the covalently bound adduct than in the more loosely bound transition state (cf. the relative trends of k_4 and K_4 constants on going from the cation **3a** to **4a**). It would seem that while the rate constants decrease rather regularly on increasing the steric hindrance of the groups, the equilibrium constants show the existence of a limit value of steric hindrance under which no steric interactions occur. However, when this limit would be overwhelmed steric interactions would increase much more steeply in the 4*H* adducts than in the corresponding transition states. This picture is consistent with the Ritchie's observation[1c] that steric effects on the equilibrium formation of the crowded triarylmethyl cation–secondary amine adducts are much greater than the steric effects on the corresponding rates. This is a case in which, overcrowding disfavors the adducts more than the transition states. The opposite would occur, in our opinion, with a lower degree of crowding. However, at present our rationalization of steric effects in cation–anion combination reactions is somewhat speculative, and further experimental data with different nucleophiles would be required to generalize the present results.

Experimental Section

Materials. Methanol-d_4 for NMR spectroscopy was from Merck. Dry methanol was obtained as previously reported.[14] Stock solutions of sodium methoxide were prepared by dissolving the appropriate amount of clean sodium in methanol (or methanol-d_4) under an argon atmosphere. Methanolic $HClO_4$ was prepared by a published procedure.[15] Purification of triethylamine and preparation of triethylamine/triethylammonium buffers were carried out as previously indicated.[14] Chloroacetic acid (Aldrich Gold Label) was used without further purification. Chloroacetic acid/chloroacetate buffers were prepared by partial

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J. Org. Chem. **1988**, *53*, 1733–1736 **1733**

neutralization of the acid with sodium methoxide solutions.

2,6-Di-*tert*-butylpyrylium perchlorate (**1a**),[4] 2,6-di-*tert*-butyl-4-methylpyrylium fluoroborate (**2a**),[16] 2,4,6-tri-*tert*-butylpyrylium perchlorate (**3a**),[4] and 2,6-di-*tert*-butyl-4-(1,1-diethylpropyl)-pyrylium perchlorate (**4a**)[17] were available from our previous work.

^{1}H NMR Measurements. Spectra were recorded on a Bruker WP 80 SY spectrometer. Low-temperature (−40 °C) and room-temperature (25 °C) ^{1}H NMR measurements for the reaction of the cation **2a** with CD_3ONa in CD_3OD, were carried out according to the procedure previously described.[4]

The ^{1}H NMR shifts relative to TMS for **2a–d** in methanol solution are as follows.

2a: δ 1.53 (s, 18 H, *t*-Bu), 2.80 (s, 3 H, Me), 8.01 (s, 2 H, H-3).

2b:[18] δ 1.18 (s, 18 H, *t*-Bu), 1.31 (s, 3 H, Me), 4.56 (s, 2 H, H-3).

2c:[18] δ 0.93 (s, 9 H, 2-*t*-Bu), 1.15 (s, 9 H, 6-*t*-Bu), 1.83 (d, 3 H, $J_{\text{H-3,Me}}$ = 1.41 Hz, Me), 4.88 (m, 1 H, $J_{\text{H-3,H-5}}$ = 1.32 Hz, $J_{\text{H-3,Me}}$ = 1.41 Hz, H-3), 4.92 (d, 1 H, $J_{\text{H-3,H-5}}$ = 1.32 Hz, H-5).

2d: δ 1.14 (s, 18 H, *t*-Bu), 4.07 (s, 2 H, CH_2), 5.51 (s, 2 H, H-3).

Rate Measurements. Kinetic experiments were carried out on a Durrum 110 stopped-flow spectrophotometer or on a Cary 219 spectrophotometer, at 25.0 °C, under pseudo-first-order conditions, with MeONa or Et_3N/Et_3NH^+ buffers in methanol. The methoxide ion concentrations of each buffer was calculated from the pK_a value of Et_3N (10.88)[15] and from the methanol autoprotolysis constant (pK_{MeOH} = 16.92).[19] Substrate concentrations were in the range (1–4) × 10^{-5} M. Ionic strength was 5 × 10^{-3} M in the case of the cation **1a** and lower than 1 × 10^{-3} M with the other cations. The reaction solutions were freshly prepared and handled under argon.

In the case of the cations **1a**, **3a**, and **4a** two widely separated first-order process were monitored. In the case of the cation **2a** only the first process, relative to the 4*H* adduct formation, was investigated. The reactions were monitored at the following wavelengths: **1a**, 293 (τ_1), 275 nm (τ_2); **2a**, 287 nm (τ_1); **3a**, 290 nm (τ_1 and τ_2); **4a**, 290 (τ_1), 280 nm (τ_2).

At the wavelengths where τ_2 was monitored the 4*H* adduct does not absorb; therefore these were the wavelengths of choice for the evaluation of the k_4/k_2 ratio for the cations **3a** and **4a**, according to eq 6.

Equilibrium Measurements. The equilibrium constants K_4 for the cations **1a** and **2a** were determined at 25.0 °C on a Durrum 110 stopped-flow. The reactions were carried out at MeO^- concentrations low enough to leave a detectable amount of the substrate in equilibrium with the 4*H* adduct at the end of the first process. The buffers used were $ClCH_2CO_2H/ClCH_2CO_2^-$ (pK_a = 7.7)[20] for the cation **1a**, and Et_3N/Et_3NH^+ for the cation **2a**. Measurements of the absorbance of the substrate at zero time (OD_0) and at the end of the first process ($OD_{\infty1}$) afforded the equilibrium constant K_4 by eq 12.

$$K_4 = \frac{(OD_0 - OD_{\infty1})}{OD_{\infty1}[MeO^-]} \qquad (12)$$

The equilibrium constants K_2 for the cations **1a**, **3a**, and **4a** were determined at 25.0 °C on a Cary 219 spectrophotometer, by measuring the residual absorbance of the substrate ($OD_{\infty2}$) after equilibration with $ClCH_2CO_2H/ClCH_2CO_2^-$ buffers. The addition of an excess of methanolic $HClO_4$ to these mixtures shifts the equilibrium completely toward the substrate, thus permitting the measurement of OD_0, after correction of the observed OD value for dilution. The $OD_{\infty2}$ values are contaminated by a small absorbance contribution due to the 2*H* adducts and must be corrected by eq 13, where ϵ_s and ϵ_{2H} are the molar absorbances of

$$OD_{\infty2}{}^c = \frac{OD_{\infty2}\epsilon_s - OD_0\epsilon_{2H}}{\epsilon_s - \epsilon_{2H}} \qquad (13)$$

the substrate and of the 2*H* adduct, respectively. The K_2 constants were obtained by eq 14. The concentration of the substrates was

$$K_2 = \frac{(OD_0 - OD_{\infty2}{}^c)}{OD_{\infty2}{}^c[MeO^-]} \qquad (14)$$

in the range (1–5) × 10^{-5} M. Ionic strength was always lower than 3 × 10^{-3} M. The absorbance measurements were carried out with Teflon-stoppered 4-cm quartz cells for the cation **1a** and 1-cm quartz cells for the cations **3a** and **4a**.

Acknowledgment. Partial Financial Support by the Ministero della Pubblica Istruzione, Roma, is greatly acknowledged.

Registry No. **1a**, 50478-27-8; **1b**, 104086-47-7; **2a**, 46426-69-1; **2b**, 112321-29-6; **2d**, 112321-31-0; **3a**, 46914-07-2; **3b**, 104086-42-2; **3c**, 104086-26-2; **4a**, 104086-48-8; **4b**, 112321-30-9; **4c**, 104086-27-3; **5a**, 75882-53-0; **5b**, 104086-44-4; **5c**, 81128-16-7; MeO^-, 3315-60-4.

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Ring-Opening Reactions. 5.[1] Elimination vs Substitution in the Cleavage of 1,1,2,2,3,3-Hexamethylaziridinium Ion

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Received May 21, 1987

The syntheses of the highly strained 1,2,2,3,3-pentamethylaziridine and 1,1,2,2,3,3-hexamethylaziridinium triflate, iodide, and perchlorate are reported. Reaction of hexamethylaziridinium triflate with $NaOCD_3$ in CD_3OD at 50 °C yields two ring-opened products in a ratio of 2:1 that result from competing substitution and elimination reactions. The changes in relative reactivity of progressively more methylated aziridinium ions with sodium methoxide in methanol are attributed to a significant reduction of nonbonded interactions in the transition state of the S_N2 opening of a small ring combined with a presumably loose transition state.

In studies of the effects of strain and stereochemical factors on the ring-opening reactions of cyclic ammonium ions,[1] we have reported that *cis*-1,1,2,3-tetramethylaziridinium ion (**1**) is cleaved by sodium methoxide in

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