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(9) Cleavage of the bond between C-1 and C-2 of the side chain of 1-phenylbutane-*1*-^{13}C produces the tropylium ion ($C_7H_7^+$, *m/e* 91, and $C_6{}^{13}CH_7$, *m/e* 92) fragment without prior scrambling of C-1 and C-2.

(10) A. A. Khalaf, Ph.D. Dissertation, The University of Texas, Austin, Texas, 1965, pp 77–80.

(11) The strong inhibitory action of these disproportionation products may also explain why 1-phenylbutane underwent less *fragmentation* than 1-phenylpropane when the compounds were treated with aluminum chloride in the absence of solvent (disproportionation conditions) by Roberts, Baylis, and Fonken.[12]

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(13) "No great difference in rate between methyl and ethyl shifts" was observed in superacid medium: D. M. Brouwer and H. Hogeveen, *Prog. Phys. Org. Chem.*, **9**, 213 (1972).

(14) (a) R. M. Roberts and R. N. Greene, *Acta Cient. Venez.*, **15**, 251 (1965); (b) R. N. Greene, Ph.D. Dissertation, The University of Texas at Austin, 1965.

(15) Tributylbenzenes were also produced, but they and other higher molecular weight compounds were not included in calculations of the distributions of products.

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Nucleophilic Substitution in the Side Chain of Five-Membered Heterocycles. 3. Reactions of Heterocyclic Aldehydes with Aniline and with Benzoylmethylenetriphenylphosphorane

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The rate constants for the reactions of five-membered heteroaromatic aldehydes with aniline in acetonitrile (Schiff reaction) and with benzoylmethylenetriphenylphosphorane in methanol (Wittig reaction) were measured in order to attempt structure–reactivity correlations. The observed reactivity sequence (2-furyl > phenyl > 2-thienyl > 2-pyrrolyl) is the same as previously found in other substitutions at the carbonyl group. The electron-donating character of the heteroatoms in the Schiff reaction is proved by the Hammett treatment of the data. However, extension of this treatment to other reactions at the carbonyl group does not give constant σ_{het} values. Application of the Taft–Pavelich eqation points out a dependence of the rate of reaction on polar and steric effects of heteroaromatic rings. Information from Hammett and Taft–Pavelich equations, however, is not unequivocal owing to inherent features of both free-energy relationships.

In previous articles of this series kinetic data for the reactions of arylmethyl chlorides[1] and arenesulfonyl chlorides[2] with aniline were reported, in order to correlate the reactivity of five-membered heterocycles with that of benzene derivatives and to attempt structure–reactivity correlations. However, no generalization was drawn owing to different behavior of heterocyclic compounds in different kinds of reactions.

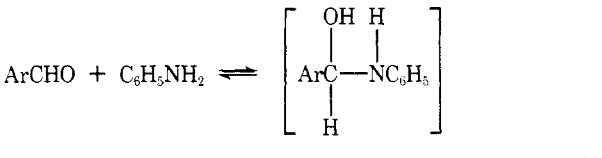
In fact, the reactivity sequence (2-furyl > 2-thienyl > phenyl) observed for the reaction of arylmethyl chlorides with aniline[1] appears to be in agreement with the polarity of heterocycles, given by σ^* values,[3] while the rate sequence for the reaction of arenesulfonyl chlorides with aniline[2] (phenyl > 2-furyl > 2-thienyl) suggests that the conjugative effect, described by σ^+ values, appears to be prevailing.[4,5]

Moreover, a different reactivity sequence (2-furyl > phenyl > 2-thienyl) is observed in some nucleophilic substitutions at the carbonyl group, as in the reaction of arylcarbonyl chlorides with aniline,[6] of aryl chloromethyl ketones with triethyl phosphite,[7] in the alkaline hydrolysis of esters[3] and in the reduction of aryl methyl ketones by sodium borohydride.[8] This fact might formally derive from the balance between the opposite electronic effects in the five-membered heterocycles (−I, +M), even if the role of steric factors in some of these reactions cannot be neglected.[3,9]

To verify the specificity of this sequence for reactions at the carbonyl group, we here report kinetic data relative to the reactions of heterocyclic aldehydes with aniline (Schiff reaction), and with benzoylmethylenetriphenylphosphorane (BMTPP) (Wittig reaction). In this paper we intend also to rationalize the data on nucleophilic substitutions at the carbonyl group in the side chain of five-membered heterocycles, using free-energy relationships.

Results

Reactions of Aldehydes with Anilines. The Schiff base formation from aromatic aldehydes and amines (reaction 1) is a well-known two-step addition–elimination reaction, in which the rate-determining step depends on the aromatic ring structure and on experimental conditions (solvent, pH).[10–12]



$$\mathrm{ArCHO} + \mathrm{C_6H_5NH_2} \rightleftharpoons \left[\mathrm{Ar}\overset{\mathrm{OH}}{\underset{\mathrm{H}}{\mathrm{C}}}-\overset{\mathrm{H}}{\mathrm{N}}\mathrm{C_6H_5}\right] \rightleftharpoons \mathrm{ArCH{=}NC_6H_5} + \mathrm{H_2O} \quad (1)$$

Ar = 2-C_4H_3S, 2-C_4H_3NH, *p*-$(CH_3)_2NC_6H_4$, *p*-$CH_3OC_6H_4$, *p*-$CH_3C_6H_4$, *p*-ClC_6H_4, *p*-$O_2NC_6H_4$

Acetonitrile was chosen as a solvent because, being dipolar, it allows an appreciably fast kinetics in the absence of catalyst; moreover, being aprotic, it prevents the hydrolysis of the Schiff bases, a phenomenon that would not give quantitative yields.[13]

The reaction was followed by monitoring the UV absorbance of the Schiff base (see Experimental Section). The kinetics is second order overall, first order with respect to each reactant, as expected for an uncatalyzed reaction, according to the simple rate law

$$\text{rate} = k_2[\text{aldehyde}][\text{nucleophile}] \qquad (2)$$

Rate constants at 25 °C are reported in Table I, showing that the reactivity sequence is the following: phenyl > 2-thienyl > 2-pyrrolyl. The k_2 value for 2-furaldehyde is not re-

Table I. Second-Order Rate Constants for the Reactions of RCHO with Aniline in Acetonitrile at 25 °C

Registry no.	R	10^5k_2, L mol^{-1} s^{-1} [a]
100-52-7	C_6H_5	72.0
104-88-1	p-ClC_6H_4	45.8
104-87-0	p-$CH_3C_6H_4$	13.9
123-11-5	p-$CH_3OC_6H_4$	7.34
555-16-8	p-$O_2NC_6H_4$	4.49
98-03-3	2-C_4H_3S	2.64
1003-29-8	2-C_4H_3NH	0.0452
100-10-7	p-$(CH_3)_2NC_6H_4$	0.0254

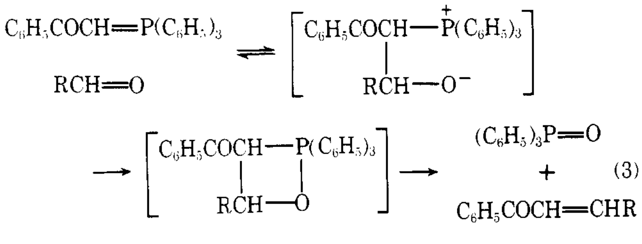
[a] Maximum error ±7%.

ported, as the Schiff base is not formed quantitatively, owing to the occurrence of competitive and consecutive reactions.[14]

The Hammett plot for para-substituted benzaldehydes is not linear, showing a rate maximum near the point for benzaldehyde (Figure 1).

This behavior, already observed for the reactions of benzaldehydes with n-butylamine in methanol,[10] with aniline in water (pH 6.1),[12] and with p-toluidine in ethanol and in benzene,[15] is due to the influence of substituents on both steps (reaction 1): electron-donating groups (ρ positive) decrease the nucleophilic attack rate (first step), while electron-withdrawing ones (ρ negative) reduce the carbinolamine dehydration (second step); thus, these effects cause a variation in the rate-limiting step.

Reactions of Aldehydes with BMTPP. The synthesis of olefins from carbonyl derivatives and phosphorus stable ylides (Wittig reaction) is a nucleophilic substitution in which the rate-determining step is the attack of a carbanion to the carbonyl carbon atom, followed by the stepwise formation of a betaine and a four-membered intermediate (eq. 3).[16]



$$\begin{array}{c} C_6H_5COCH{=}P(C_6H_5)_3 \\ RCH{=}O \end{array} \rightleftharpoons \left[\begin{array}{c} C_6H_5COCH-\overset{+}{P}(C_6H_5)_3 \\ | \\ RCH-O^- \end{array}\right] \longrightarrow \left[\begin{array}{c} C_6H_5COCH-P(C_6H_5)_3 \\ |\qquad\quad | \\ RCH-O \end{array}\right] \longrightarrow \begin{array}{c} (C_6H_5)_3P{=}O \\ + \\ C_6H_5COCH{=}CHR \end{array} \quad (3)$$

R = 2-C_4H_3O, 2-C_4H_3S, 2-C_4H_3NH, C_6H_5, c-C_6H_{11}

BMTPP is a stable ylide, easily workable, and for this reason it was chosen as a reagent. The reaction, carried out in methanol, yields chalcone analogues quantitatively and was followed by titration of the residue ylide in the presence of an indicator (see Experimental Section). In all cases, an overall second-order kinetics, first order with respect to each reactant (eq 2), was observed. In Table II the rate constants and the activation parameters are reported.

The reactivity sequence (2-furyl > phenyl > 2-thienyl > 2-pyrrolyl) is analogous to that already observed for other nucleophilic reactions at the carbonyl group.[3,6-8]

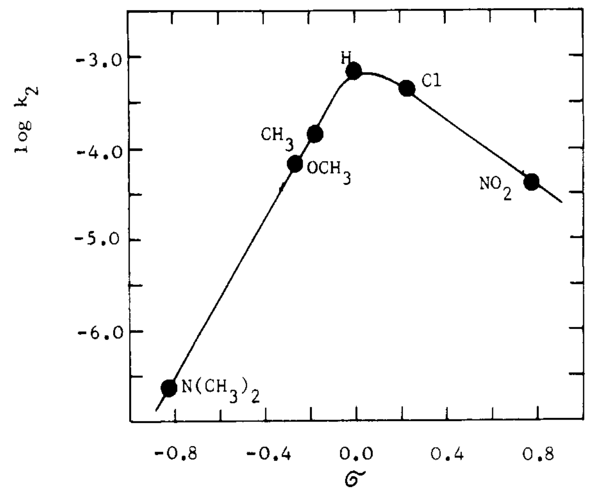


Figure 1. Hammett plot for the reactions of para-substituted benzaldehydes with aniline in acetonitrile at 25 °C.

Discussion

Application of the Hammett Equation. Application of the Hammett equation to equilibrium or reactivity data of five-membered heterocycles provides information on the electronic effects of heteroatoms.[5,17] In fact, if we consider the heterocycle as a substituted benzene, σ_{het} constants for the replacement of a CH=CH group in the benzene ring by the heteroatom can be calculated by eq 4, using the appropriate ρ and $\log k_0$ values:

$$\sigma_{het} = (\log k - \log k_0)/\rho \qquad (4)$$

The electron-donating effect of the heteroatom is evident in the Schiff reaction,[18] as shown by the negative $\sigma_{2\text{-}S}$ and $\sigma_{2\text{-}NH}$ values (Table III).

Actually, in the case of five-membered rings, variable σ_{het} values can be derived from other reaction systems,[19] while a high degree of consistency of σ_{het} from pyridine derivatives is observed.[5]

The Hammett treatment was also applied to the available data for nucleophilic substitutions at carbonyl group. Results reported in Table III show the variability of σ_{het} values, also in the case of reactions at the carbonyl group only. Particularly, the 2-furyl group acts as benzene ($\sigma_{2\text{-}O}$ zero) in reactions 2 and 5, and as an electron-withdrawing group in 3, 4, and 6; 3-furyl and 3-thienyl groups show strong resemblances with benzene, except in reaction 5; σ_{het} for 2- and 3-pyrrolyl groups, instead, appear to be more consistent.

The wide variability of σ_{het} can be ascribed to the polarizability of five-membered heterocycles, whose ability to induce through-conjugation is well known.[20] Hence some authors[8,21] used the Yukawa–Tsuno equation (5) to rationalize reactivity data:

$$\log k/k_0 = \rho[\sigma_{het} + r(\sigma^+_{het} - \sigma_{het})] \qquad (5)$$

However, while σ^+_{het} values are constant, as is proven by extended selectivity treatment,[22] the choice of a particular set

Table II. Second-Order Rate Constants and Activation Parameters for the Reactions of RCHO with BMTPP in Methanol

Registry no.	R	10^3k_2, L mol^{-1} s^{-1} [a] 35 °C	45 °C	60 °C	$\Delta H^{\ddagger}$, kcal mol^{-1}	$-\Delta S^{\ddagger}$, cal mol^{-1} K^{-1}
98-01-1	2-C_4H_3O	2.90	5.14	9.95	9.4	39.7
	C_6H_5	1.04	2.06	4.26	10.8	37.3
	2-C_4H_3S	0.54	0.97	2.56	12.2	34.2
2043-61-0	c-C_6H_{11}	0.081	0.18	0.48	13.9	29.4
	2-C_4H_3NH	0.023	0.038	0.12	13.1	37.6

[a] Maximum error ±6%.

Table III. Application of the Hammett Equation to Reactions at the Carbonyl Group and Substituent Constants for Heteroatoms in Five-Membered Rings

					σ_{het}[d]						
Reaction or equilibrium	X[a]	r[b]	ρ[c]	Log k_0[c] (or pK_0)	2-O	3-O	2-S	3-S	2-NH	3-NH	Ref[e]
1. $XC_6H_4CHO + C_6H_5NH_2$[f] (acetonitrile, 25 °C)	1, 2, 3, 4	0.999	4.18 (0.14)	−3.11 (0.06)			−0.35		−0.83		*f*
2. $XC_6H_4CHO + OH^-$[g] (p*K*, water, 25 °C)	1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 12	0.994	−2.76 (0.05)	14.98 (0.10)	0.08		−0.085		<−0.73		*h*
3. $XC_6H_4COCH_2Cl + (C_2H_5O)_3P$[i] (benzene, 40 °C)	1, 2, 3, 5, 6	0.997	1.88 (0.08)	−4.13 (0.03)	0.43	0.01	−0.16	−0.01			*j*
4. $XC_6H_4COCl + C_6H_5NH_2$[k] (benzene, 25 °C)	1, 2, 3, 5,7, 13, 14, 15	0.978	1.42 (0.12)	−1.31 (0.03)	0.31	−0.05	−0.20	−0.04			*l*
5. $XC_6H_4COCH_3 + NaBH_4$[m] (2-propanol, 30 °C)	1, 2, 3, 4, 5, 7, 9, 13, 14, 16, 17, 18	0.987	2.84 (0.15)	−2.75 (0.06)	0.06	−0.16	−0.16	−0.11	−0.79	−0.93	*n*
6. $XC_6H_4COOC_2H_5 + OH^-$[o] (62% aq acetone, 25 °C)	1, 2, 6, 7, 10, 16, 19	0.999	2.37 (0.06)	−2.51 (0.03)	0.27	0.03	0.01	0.00	−0.58[q]	−0.94[q]	*p*

[a] Key for X substituent: 1, H; 2, *p*-CH_3; 3, *p*-OCH_3; 4, *p*-$N(CH_3)_2$; 5, *p*-Cl; 6, *p*-NO_2; 7, *m*-CH_3; 8, *m*-OCH_3; 9, *m*-Cl; 10, *m*-NO_2; 11, *m*-CN; 12, *p*-CN; 13, *p*-Br; 14, *m*-Br; 15, *m*-I; 16, *p*-NH_2; 17, *p*-F; 18, *m*-F; 19, *m*-NH_2. [b] Correlation coefficient. [c] Standard deviation of the estimate in parentheses. [d] Standard deviation of σ_{het} ranges from 0.05 to 0.08. [e] References for reactivity data of heterocyclic compounds. [f] This work. [g] W. J. Bover and P. Zuman, *J. Chem. Soc., Perkin Trans. 2,* 786 (1973). [h] W. J. Scott, W. J. Bover, K. Breatin, and P. Zuman, *J. Org. Chem.*, **41**, 1952 (1976). [i] A. Arcoria and S. Fisichella, *Tetrahedron Lett.*, 3347 (1971). [j] Reference 7. [k] R. A. Benkeser, C. E. DeBoer, R. E. Robinson, and D. M. Sauve, *J. Am. Chem. Soc.*, **78**, 682 (1956). [l] Reference 6. [m] Reference 8, 9. [n] Reference 8. [o] E. Tommila and C. N. Hinshelwood, *J. Chem. Soc.*, 1801 (1938). [p] Reference 3; M. K. A. Khan and K. J. Morgan, *Tetrahedron*, **21,** 2197 (1965). [q] Reported from ref 8.

Table IV. Data Used and Results of Correlations with Equation 6

	X	C_6H_5	2-C_4H_3O	3-C_4H_3O	2-C_4H_3S	3-C_4H_3S			Log k_0[b]
Equilibrium or reaction σ^*[c]	σ^*[c]	0.60	1.08	0.65	0.93	0.65	r[a]	ρ[b]	(or pK_0)
pK_a XCOOH (water, 25 °C)[c]		4.21	3.16	3.95	3.53	4.10	0.988	−2.04 (0.18)	5.39 (0.15)
pK_a $XB(OH)_2$ (water, 25 °C)[d]		8.83	7.88	8.65	8.11	8.77	0.993	−2.00 (0.14)	10.0 (0.11)
pK_a XSO_2NHR (50% aq ethanol, 20 °C)[e]									
R = H		11.33	10.39		10.76	11.20	0.995	−1.87 (0.13)	12.44 (0.11)
R = C_6H_5[f]		9.98	9.02		9.41	9.83	0.982	−2.05 (0.16)	11.28 (0.18)
R = $CH_2C_6H_5$		12.53	11.54		11.93	12.47	0.997	−2.05 (0.12)	13.79 (0.10)
Rearrangement $XCH(OH)CH{=}CHCH_3$[g]									
(log k_2 rel, 60% aq dioxane, 30 °C)		0.00	1.95		1.54		0.994	4.16 (0.46)	−2.45 (0.41)
Isomerization *cis*-$XCH{=}CHC_6H_5$[h]									
(log k_1, decalin, 170 °C)		−2.21	−0.98		−1.32		0.999	2.58 (0.10)	−3.75 (0.09)
Reaction $XCH_2Cl + C_6H_5NH_2$[i]									
(log k_3, acetonitrile, 50 °C)		−4.39	−3.61		−3.75		0.990	1.68 (0.24)	−5.38 (0.21)
(log k_3, benzene, 50 °C)		−6.58	−4.78		−5.46		0.997	3.69 (0.27)	−8.82 (0.24)
Alkaline hydrolysis $XCONHC_6H_5$[j]									
(log k_1, 76% aq ethanol, 100 °C)		−4.59	−4.00	−4.56	−4.24	−4.51	0.994	1.19 (0.08)	−5.31 (0.06)
Rearrangement XCOCOY[k]									
(log k_2, 67% aq dioxane, 50 °C)			−4.00	−3.73	−3.43	−2.91	0.995	1.59 (0.11)	−5.85 (0.17)
($\sigma_X^* + \sigma_Y^*$)			(1.20)	(1.30)	(1.53)	(1.86)			

[a] Correlation coefficient. [b] Standard deviation of the estimate in parentheses. [c] Reference 3. [d] B. P. Roques, D. Florentin, and M. Callanquin, *J. Heterocycl. Chem.*, **12,** 195 (1975). [e] A. Ballistreri, E. Maccarone, and G. Musumarra, *J. Chem. Soc., Perkin Trans. 2,* 984 (1977). [f] The correlation includes pK_a of the following 5-Y-2-$C_4H_2SO_2NHC_6H_5$ (Y, pK_a,[e] σ^*[c]): CH_3, 9.65, 0.84; Cl, 8.84, 1.26; Br, 8.84, 1.29; NO_2, 7.68, 1.65. [g] E. A. Braude and J. S. Fawcett, *J. Chem. Soc.*, 4158 (1952). [h] G. Scarlata and M. Torre, *J. Heterocycl. Chem.*, **13,** 1193 (1976). [i] Reference 1. [j] Reference 26. [k] G. P. Nilles and R. D. Schuetz, *J. Org. Chem.*, **36,** 2489 (1971).

of σ_{het} values, which is of doubtful general validity, can undergo some criticism.[5]

For this reason, combination of electronic effects as in eq 5 does not appear to be formally appropriate in order to interpret the reactivity data, and we believe that a different approach is necessary to rationalize the behavior of five-membered heterocycles in nucleophilic substitutions at the carbonyl group.

Application of the Taft Equation. Ten Thije and Janssen[3] pointed out in 1965 that failure of the Hammett equation might be expected for 2-substituted five-membered rings, owing to the proximity of the substituent to the side chain. Consequently, they proposed to correlate the data by the Taft equation (6)

$$\log k/k_0 = \rho^*\sigma^* \qquad (6)$$

and derived σ^* values for the heterocycles, following the standard conditions originally suggested by Taft.[23]

Recently, Tomasik and Johnson restricted the derivation of σ values for heteroatoms in such rings to cases where steric interactions with the reaction site appear to be absent.[5] The different geometry of five-membered rings can in fact influence differently the stability of the transition state. Specifically, in substitutions at the carbonyl group, the carbon atom which is sp^2 planar trigonal in the initial state becomes a sp^3 tetrahedral carbon atom in the transition state. The bond angles are drastically reduced from about 120° to about 109°, and the reaction rate will then be decreased because of the

Table V. Data Used and Results of Correlations with Equation 7

Reaction or equilibrium	X	C_6H_5	2-C_4H_3O	3-C_4H_3O	2-C_4H_3S	3-C_4H_3S	2-C_4H_3-NH	ρ[a]	δ[a]	Log k_0[a] (or pK_0)
	σ^*[b]	0.60	1.08	0.65	0.93	0.65	0.46[c]			
	E_s[b]	−2.55	−3.16	−2.71	−3.39	−2.73	−3.88[d]			
1. XCHO + $C_6H_5NH_2$ (log k_2, acetonitrile, 25 °C)[e]		−3.14			−4.58		−6.34	1.39	2.26	1.79
2. XCHO + BMTPP (log k_2, methanol, 35 °C)[e,f]		−2.98	−2.54		−3.27		−4.64[g]	2.58 (0.30)	0.72 (0.14)	−3.03 (0.30)
3. XCHO + OH^- (pK, water, 25 °C)[h]		14.9	14.75		15.21		17	−2.28 (0.13)	−1.30 (0.09)	13.00 (0.20)
4. $XCOCH_2Cl + (C_2H_5O)_3P$ (log k_2, benzene, 40 °C)[i]		−4.05	−3.31	−4.10	−4.43	−4.15		4.12 (0.09)	2.10 (0.06)	−1.09 (0.12)
5. XCOCl + $C_6H_5NH_2$ (log k_2, benzene, 25 °C)[j,k]		−1.20	−0.876	−1.39	−1.59	−1.36		1.52 (0.12)	1.03 (0.11)	0.49 (0.23)
6. XCOCl + m-$NO_2C_6H_4NH_2$ (log k_2, benzene, 20 °C)[l]		−3.49	−3.24[m,n]	−3.80[m,n]		−3.69[n,o]		1.18 (0.09)	1.01 (0.06)	−1.55 (0.10)
7. $XCOCH_3 + NaBH_4$ (log k_2, 2-propanol, 50 °C)[p,q]		−2.19	−1.99	−2.53	−2.51	−2.39	−4.45	2.55 (0.14)	0.98 (0.04)	−1.54 (0.09)

[a] Standard deviation of the estimate in parentheses. [b] Reference 3. [c] Obtained from the equation $\sigma^* = (pK_a - pK_{a_0})/\rho^* = (4.45 - 5.39)/-2.04$ (see Table IV). [d] Obtained by interpolation from the data of reaction 2 by the equation $E_s = (\log k_2 - \rho^*\sigma^* - \log k_0)/\delta$. [e] This work. [f] The correlation includes log k_2 for the reaction of c-$C_6H_{11}CHO$ (−4.09,[e] $\sigma^* = -0.15$, $E_s = -0.79$). [g] Not included in correlation. [h] W. J. Scott, W. J. Bover, K. Breatin, and P. Zuman, *J. Org. Chem.*, **41,** 1952 (1976); the correlation includes the pK of 5-Br-2-C_4H_2SCHO (14.64, $\sigma^* = 1.29$,[b] $E_s = -3.58$[b]). [i] Reference 7. [j] Reference 6. [k] The correlation includes log k_2 of the following 5-Y-2-C_4H_2SCOCl (Y, log k_2, σ^{*b}, $E_s{}^b$): CH_3, −1.99, 0.84, −3.58; Cl, −1.23, 1.26, −3.53; NO_2, −0.374, 1.65, −3.19. G. Alberghina, A. Arcoria, S. Fisichella, and G. Scarlata, *Gazz. Chim. Ital.*, **103,** 319 (1973). [l] The correlation includes log k_2 of the following XCOCl (X, log k_2, σ^*, E_s): CH_3, −1.91, 0.0, 0.0; n-C_3H_7, −2.02, −0.115, −0.36; n-C_4H_9, −2.17, −0.13, −0.39; i-C_4H_9, −2.42, −0.125, −0.93; $C_6H_5CH_2$, −1.68, 0.215, −0.38; $CH_3CH{=}CH$, −2.32, 0.36, −1.63; $ClCH_2$, −0.38, 1.05, −0.24; Cl_3C, −0.558, 2.65, −2.06. H. S. Venkataraman and C. N. Hinshelwood, *J. Chem. Soc.*, 4977 (1960). [m] A. Arcoria, S. Fisichella, G. Scarlata, and D. Sciotto, *J. Org. Chem.*, **39,** 3025 (1974). [n] Interpolated at 20 °C from activation parameters. [o] A. Arcoria and S. Fisichella, *J. Org. Chem.*, **38,** 3774 (1973). [p] Reference 8. [q] The correlation includes log k_2 of the following $XCOCH_3$ (X, log k_2, σ^*, E_s): CH_3, −1.68, 0.0, 0.0; C_2H_5, −1.95, −0.10, −0.07; i-C_3H_7, −2.27, −0.19, −0.47; $C_6H_5CH_2$, −1.49, 0.215, −0.37; $C_6H_5(CH_3)CH$, −2.32, 0.11, −1.19; $(C_6H_5)_2CH$, −2.40, 0.405, −1.76. H. C. Brown, R. Bernheimer, and K. J. Morgan, *J. Am. Chem. Soc.*, **87,** 1280 (1965); ref 9.

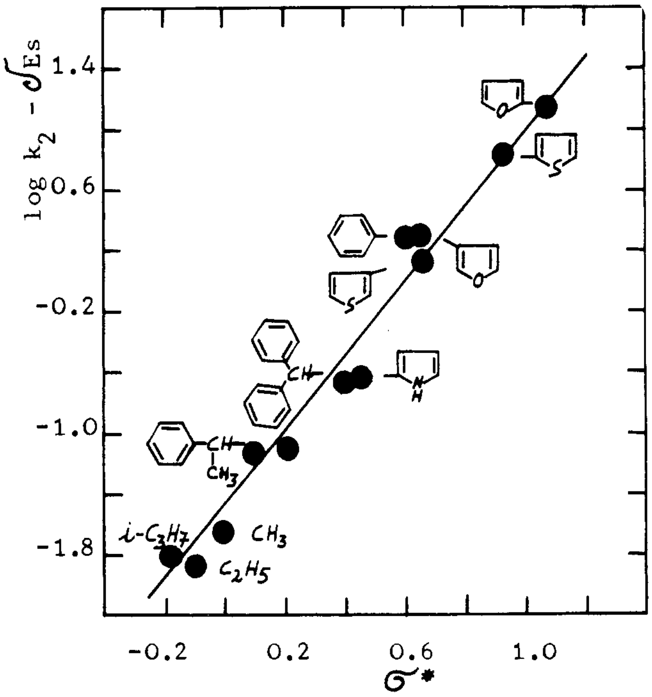


Figure 2. Application of the Taft–Pavelich equation to the reduction of $RCOCH_3$ with $NaBH_4$ in 2-propanol at 50 °C.

back strain in the transition state, due to the bulky adjacent group.

The Taft–Pavelich equation (7), which is widely used,[24] takes into account both polar (σ^*) and steric (E_s) effects, and appears to be a better model to relate the substrate structure to the carbonyl group reactivity:[25]

$$\log k/k_0 = \rho^*\sigma^* + \delta E_s \qquad (7)$$

Equation 6 was applied successfully to equilibria or reaction series in which steric hindrances are negligible, as dissociation of carboxylic acids,[3] alkaline hydrolysis of arylanilides,[26] and reactions of arylmethyl chlorides with aniline;[1] the reported results are shown in Table IV, together with other data elaborated by us.

The data for seven more reactions, for which eq 6 was unsuccessfully attempted, were satisfactorily interpreted according to eq 7, and, whenever homogeneous data were available, this equation was also successfully applied in the case of aliphatic and unsaturated compounds. Data used and results of correlations are reported in Table V.

As eq 7 correlates a wide range of data for reactions at the carbonyl group, the behavior of five-membered rings might be discussed in general terms on the basis of steric and polar effects.[27] The observed reactivities, separated from the contribution due to steric effect (log $k_2 - \delta E_s$), are in agreement with the polar effect sequence (Figure 2).

In particular, the 2-thienyl ring, which seems to behave as an electron-donating group using the Hammett treatment, appears to be an electron-withdrawing group as suggested by its σ^* values. However, a limitation to this interpretation is due to the fact that E_s values for aromatic and unsaturated groups, as well as for heterocyclic five-membered rings, include a conjugative contribution, as pointed out by Taft.[23]

In conclusion the Hammett treatment neglects the contribution due to the steric effects, while the Taft–Pavelich equation, in this case, includes conjugative effects in the steric parameter. A better model might be represented by Charton's equation (8),[25] which takes into account independent variations of inductive (σ_I), resonance (σ_R), and steric (υ) effects:

$$\log k = \alpha\sigma_I + \beta\sigma_R + \psi\upsilon + h \qquad (8)$$

Unfortunately, its application, which might provide the "weight" of each effect on the observed reactivity, is not possible at the moment owing to the lack of appropriate σ_I, σ_R, and υ values for five-membered rings.

Experimental Section

Reagents and Solvents. Aldehydes and aniline were commercial products, purified by distillation or crystallization. Solvents (acetonitrile and methanol, RPE Carlo Erba) were used without further purification.

Benzoylmethylenetriphenylphosphorane (BMTPP) was obtained by treating phenacyltriphenylphosphonium bromide with 10% aqueous sodium carbonate following the procedure already described,[28] mp 178–180 °C.

Kinetic Procedure. A. Schiff Reaction. Standard solutions of aldehyde and aniline in acetonitrile (10 mL) were mixed at 25 °C. Initial concentrations varied in the range 0.025–0.50 mol L^{-1}. At intervals, 1 mL of the reaction solution was placed in a 100-mL volumetric flask and the volume made up with acetonitrile. The optical density and the molar extinction coefficient of the Schiff bases were measured at the appropriate wavelength[29] and their concentrations calculated. The reaction follows a second-order kinetics to at least 70% completion. k_2 constants reported in Table I are average values from at least four determinations at different reagent concentrations.

B. Wittig Reaction. Standard solutions (10 mL) of ylide (0.02 mol L^{-1}) and aldehyde (0.10 mol L^{-1}) in methanol were mixed in stoppered flasks and kept at constant temperature. At intervals the flask was cooled with an ice bath and part of hydrochloric acid necessary to titrate the residue ylide added. Some drops of bromophenol blue (1/1000 v/v alcohol solution) were then added and the ylide titrated with HCl until greenish color was observed. In all cases the reactions followed a second-order kinetics. The rate constants were calculated by

$$k_2 = 2.303/4at \log[(5a - x)/5(a - x)] \qquad (9)$$

where a is the ylide concentration (0.02 mol L^{-1}) and x the reacted amount at time t.

Reaction Products. Schiff Bases. Equimolar amounts of aldehyde and aniline (0.10 mol) were allowed to react in acetonitrile (100 mL) at room temperature for 6–48 h, depending on the aldehyde reactivity. Acetonitrile was evaporated and the residue distilled under vacuum or crystallized from petroleum ether (bp 30–60 °C) or absolute ethanol, yield >90%. $RCH{=}NC_6H_5$ [R, bp (mmHg) or mp]: C_6H_5, 50–51 °C;[30] p-$CH_3C_6H_4$, 150 °C (0.2), 43 °C;[31] p-$CH_3OC_6H_4$, 176 °C (1.0), 63 °C;[31] p-$(CH_3)_2NC_6H_4$, 99 °C;[31] p-ClC_6H_4, 63 °C;[31,32] p-NO_2, 90 °C;[31,32] 2-C_4H_3S, 109–110 °C (0.1);[33] 2-C_4H_3NH, 92–93 °C.[34]

Chalcones. Solutions of BMTPP and aldehyde in methanol were allowed to react at 50 °C for about 24 h. After evaporation of the solvent the residue was distilled or crystallized from petroleum ether or absolute ethanol, yield > 80%. $RCH{=}CHCOC_6H_5$ [R, bp (mmHg) or mp]: C_6H_5, 57–58 °C;[35] 2-C_4H_3O, 171 °C (3);[36,37] 2-C_4H_3S, 58–59 °C;[37] 2-C_4H_3NH, 138–139 °C;[38] c-C_6H_{11}, 167–168 °C.[39]

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Registry No.—Aniline, 62-53-3; BMTPP, 859-65-4.

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