Bull. Chem. Soc. Jpn., 60, 1097—1101 (1987)

Substituent Effects. XVII.[1] Rearrangement in the Acetolysis of 2-Arylethyl Tosylates[2]

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(Received October 16, 1986)

The label scrambling within the ethylene chain of the final acetolysis products was determined for a series of α-D_2 labeled 2-arylethyl tosylates by using proton NMR spectroscopy and the k_Δ/k_s values were derived from the scrambling ratios. For both buffered and unbuffered acetolysis runs $\log(k_\Delta/k_s)$ were not correlated linearly with σ° or σ^+. Application of the LArSR Eq. results in linear correlations with excellent precision, $\log(k_\Delta/k_s)=-3.70\ (\sigma^\circ+0.63\Delta\bar{\sigma}_R^+)+0.152$ for the unbuffered run and $\log(k_\Delta/k_s)=-3.97\ (\sigma^\circ+0.60\Delta\bar{\sigma}_R^+)-0.207$ for the buffered run. The ρ_Δ and r_Δ values for the aryl-assisted pathway are estimated from the above apparent values based on the reasonable assumption of small ρ_s values for the k_s pathway.

The foregoing papers[1,3] described the dissection of the substituent effect on the acetolysis of 2-arylethyl tosylates into the effects on solvent-assisted (k_s) and anchimerically assisted (Fk_Δ) processes.[4] The dissection was based upon an assumption of the LArSR relationship (1)[5]

$$\log(k/k_o) = \rho(\sigma^\circ + r\Delta\bar{\sigma}_R^+) \tag{1}$$

for the respective substituent effects on the two competing processes. While the validity of the individual correlation was supported by the agreement with other experimental facts,[6] convincing evidence would be provided by a direct application of the LArSR relationship to the substituent effect on each process having been separated by a technique independent of the substituent effect analysis.

A kinetic analysis of the respective processes of the acetolysis of 2-arylethyl tosylates was accomplished by using ^{13}C tracer method for typical substituted derivatives.[2,7] Unfortunately, however, the substituents studied are inevitably limited and insufficient to attain a detailed correlation analysis of the substituent effects.

Among the pertinent quantities obtained in these tracer studies, the aryl rearrangement ratio in the product at $t=\infty$ is the useful quantity which can be determined most easily by using the α- or β-methylene-labeled compounds. This can be related directly to the rate ratio k_Δ/k_s by Eq. 2, based on the Winstein-Coke scheme of this reaction,[8a,9] as

$$k_\Delta/k_s = \frac{[\%\text{Rearrangement ROAc } (t=\infty)]}{50-[\%\text{Rearrangement ROAc } (t=\infty)]} \tag{2}$$

The substituent effect on the k_Δ/k_s value may be simply given as the difference of two linear Hammett relations for the k_Δ and k_s processes.

$$\log(k_\Delta/k_s)_X - \log(k_\Delta/k_s)_H = \log(k_X/k_H)_\Delta - \log(k_X/k_H)_s$$
$$= \rho_\Delta\bar{\sigma}_\Delta - \rho_s\bar{\sigma}_s$$

where $\bar{\sigma}_\Delta$ and $\bar{\sigma}_s$ are the substituent constants appropriate for k_Δ and k_s processes, respectively. Furthermore, from the additivity of the LArSR correlations, the overall substituent effect on the k_Δ/k_s quantity will be treated totally as a single linear LArSR correlation. Thus the k_Δ/k_s substituent effect is quite different from the nonlinear behavior of the k_t substituent effect in the foregoing analysis.[1,3] Nevertheless, both quantities are only different functions of the same rate parameters, and hence a comparative analysis will give further information concerning the intrinsic substituent effect on respective processes.

Results

The label scrambling in the product 2-arylethyl acetate was determined for a series of α-D_2 labeled 2-arylethyl tosylates, by using proton NMR spectroscopy. k_Δ/k_s values were derived from the scrambling ratios based on Eq. 2. The results are listed in Table 1, and compared with the results of previous ^{13}C-tracer studies.[2] The k_Δ/k_s values were determined over a range of 10^4 ranging from the p-MeO derivative solvolyzing exclusively through a k_Δ process to the m-Cl one reacting primarily through a k_s process. At both extremes of nearly complete and no scrambling, the k_Δ/k_s value should rapidly become less accurate. Thus further extention of the range of substituents was not attempted in this study, but instead, in the present set were included deactivated strong π-donors, such as 3-Cl- or 3-CN-substituted 4-methoxyphenyl and 4-(methylthio)phenyl derivatives, which were found to be particularly effective for defining the r value.[10] The addition of sodium acetate lowered the rearrangement ratio for all substrates. The k_s process rather than k_Δ process may be effectively accelerated by the addition of acetate anion, while the substituent change of the ratio remains approximately the same in both buffered and unbuffered acetolyses.

The type of change of k_Δ/k_s with substituents differs

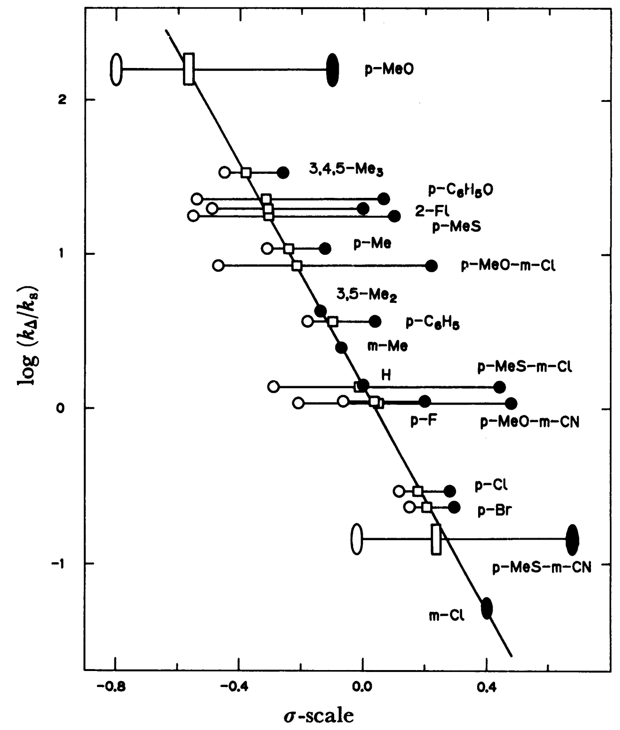

Fig. 1. The LArSR plot of log (k_Δ/k_s) for unbuffered run against σ^+ (open circles), σ° (closed circles), and $\bar{\sigma}$ for $r=0.63$ (squares).

clearly from that of k_t value. There is no simple linear logarithmic relationship between k_Δ/k_s ratios and k_t values. Figure 1 illustrates the substituent effect on log (k_Δ/k_s) quantity for the unbuffered run. Log (k_Δ/k_s) can not be correlated linearly with σ° nor with σ^+, but are linearly described in terms of the LArSR relationship. The line segments between σ° and σ^+ for para π-donors correspond to their $\Delta\bar{\sigma}_R^+$ values, and the LArSR $\bar{\sigma}$ values are represented by the points dividing these resonance segments at a unique internal ratio, which corresponds to the r value. Clearly, we see that such points (squares) with $r=0.63$ all fall on a straight line of a ρ value of -3.70 including m-substituents.

A least-squares application of LArSR Eq. 1 to the unbuffered k_Δ/k_s set results in a linear correlation (Fig. 1),

$$\log (k_\Delta/k_s)_X = -(3.70\pm0.05)(\sigma^\circ+(0.63\pm0.02)\Delta\bar{\sigma}_R^+) + 0.152 \qquad (3)$$

with an excellent precision with an R=0.9990 and a SD=±0.042. The substituent parameters used are those employed for the previous analysis.[1] Similarly, the buffered set can also be correlated by (3′)

Table 1. Rearrangement of the Acetolysis Product of 2-(Substituted Phenyl)ethyl Tosylates[a] at 115 °C

Substituent	Without NaOAc		With NaOAc (0.06 mol dm^{-3})	
	%Rearr.[b]	k_Δ/k_s[c,d]	%Rearr.[b]	k_Δ/k_s[c,d]
p-MeO	>49.7[e]	160(>125[f])	49.4±0.2	82
3,4,5-Me$_3$	48.6±0.1	34	47.3±0.3	17
p-C$_6$H$_5$O	47.9±0.1	23	45.3±0.3	9.6
2-Fluorenyl	47.6±0.2	20	45.0±0.3	9.0
p-MeS	47.4±0.3	18	44.3±0.3	7.8
p-Me	45.8±0.3	11(11)	41.7±0.3	5.0(5.8)
4-MeO-3-Cl	44.7±0.3	8.4	38.5±0.2	3.3
3,5-Me$_2$	40.7±0.3	4.4	34.6±0.2	2.2
p-C$_6$H$_5$	39.3±0.2	3.7	30.3±0.3	1.5
m-Me	35.8±0.3	2.5(2.9)	27.9±0.3	1.3(1.4)
H	29.2±0.3	1.4(1.4)	18.7±0.2	0.60(0.75)
4-MeS-3-Cl	29.0±0.2	1.4	16.9±0.1	0.51
p-F	26.5±0.3	1.1(1.2)	15.9±0.3	0.47(0.53)
4-MeO-3-CN	26.2±0.3	1.1	14.5±0.3	0.41
p-Cl	11.4±0.2	0.30(0.33)	4.9±0.2	0.11(0.13)
p-Br	9.5±0.1	0.23	4.2±0.1	0.09
4-MeS-3-CN	6.0±0.5	0.14	2.7±0.5	0.06
m-Cl	2.5±0.5	0.05(0.04)	0	—
p-NO$_2$	0	—	0	—

a) Initial concn of α,α-D$_2$-labeled tosylates, 0.02 mol dm^{-3}; determined by ^{1}H NMR. b) Rearrangement in solvolysis products at complete reaction: 100×[Rearranged acetate]/[Total acetates]. c) Derived from %Rearrangement by Eq. 2. d) Values in the bracket were determined from α-^{13}C labeled tosylates by ^{13}C NMR; Ref. 2. e) At 90 °C. f) At 75 °C.

$$\log (k_\Delta/k_s)_{AcO^-} = (-3.97\pm0.05)(\sigma^\circ + (0.60\pm0.02)\Delta\bar{\sigma}_R^+) - 0.207 \qquad (3')$$

with an excellent precision with an R=0.9988 and a SD=±0.045. Both r_Δ values are quite close to the r_Δ obtained for neophyl acetolysis.[10] Both buffered and unbuffered $\log (k_\Delta/k_s)$ sets in fact give linear plots against $\log (k_X/k_H)$ of acetolysis of neophyl brosylates (2-methyl-2-phenylpropyl *p*-bromobenzenesulfonate) with comparable slopes of approximately unity.

Discussion

The linear LArSR correlation with k_Δ/k_s quantities for the entire range of substituents contrasts sharply with the nonlinear behavior observed for the total solvolysis rate of the same reaction. The substituent effects on electrophilic reactions are generally described by the LArSR Eq. 1,[5] in which any sets of apparent substituent constants can be given in a unified manner in terms of varying r characteristic of systems. This unified description of general substituent constants leads to a unique additivity relationship of substituent effects,

$$\Sigma \log (k/k_o)_j = \Sigma\, \rho_j(\sigma^\circ + r_j\Delta\bar{\sigma}_R^+) = \rho'(\sigma^\circ + r'\Delta\bar{\sigma}_R^+) \qquad (4)$$

where $\rho'=\Sigma\rho_j$ and $r'=\Sigma\rho_j r_j/\Sigma\rho_j$. It should be noted that the overall substituent effect can be represented totally as a single linear LArSR correlation with an apparent r'. Mathematically, there is no direct way of differentiating between Eqs. 1 and 4, and of course, the apparent r' for a combined set in itself should have no direct theoretical significance. This is often an important cause of disagreement concerning the real merit of the r parameter,[11–14] as discussed further. The present quantity k_Δ/k_s can be treated, in a similar way, as the difference of the two LArSR correlations again resulting in a single linear LArSR correlation,

$$\log (k_\Delta/k_s)_X - \log (k_\Delta/k_s)_H = \rho_\Delta\bar{\sigma}_\Delta - \rho_s\bar{\sigma}_s = (\rho_\Delta - \rho_s)(\sigma^\circ + ((\rho_\Delta r_\Delta - \rho_s r_s)/(\rho_\Delta - \rho_s))\Delta\bar{\sigma}_R^+) \qquad (5)$$

The apparent ρ' and r' values of the correlation (3) should therefore be only the combined values corresponding to $\rho_\Delta - \rho_s$ and $(\rho_\Delta r_\Delta - \rho_s r_s)/(\rho_\Delta - \rho_s)$, respectively. An important key to achieving a reasonable dissection will be provided by the characteristic feature of the k_s substituent effect. From the nature of the k_s reaction, the ρ_s should be small in absolute value and the r_s to be practically unexalted (r=0). A ρ_s value of −0.19±0.04 has been estimated from the k_t effects of sufficiently deactivated derivatives.[1,3] This permits estimation of the ρ_Δ value for the aryl-assisted process to be −3.89, as $\rho_\Delta=\rho'+\rho_s$. Furthermore, because of the small ρ_s value, any conceivable exaltation in r_s does not contribute effectively to the apparent r' value. Thus setting $\rho_s r_s \rightarrow 0$ in Eq. 5 as a reasonable approximation, the r_Δ value can be estimated to be 0.60±0.03. This is essentially the same as the r_Δ value for the Fk_Δ quantity obtained from the k_t analysis.

For the buffered run, acetate ion is known to exert a significant accelerating effect on k_s pathway but no important effect on the rate of aryl-assisted ionization of typical substituted derivatives. Assuming the same ρ_Δ value as for the unbuffered run, the ρ_s can be estimated to be a small positive value of +0.08, and subsequently the r_Δ value is determined to be 0.61±0.02. In fact, a small but positive ρ_s value was observed for the acetolysis rates (k_t) of electron-attracting derivatives in the presence of sodium acetate.[15]

The inherent additivity of LArSR Eq. inevitably causes serious difficulty in dissection of the apparent LArSR correlation (3 or 3′). It should however be noted that the linear analysis applied to the k_Δ/k_s quantity would generally accomplish a correlational result of much higher precision than the nonlinear method applied to the k_t analysis. A precise linear free energy relationship is generally indicative of a fixed mechanism for the reaction. Consequently, the precise conformity to Eqs. 4 or 5 implies that both processes satisfy each individual LArSR correlation for the entire substituent range, providing evidence for the absence of any mechanistic change-over in either process.

The validity of this dissection relies essentially upon the reasonableness of requirement $|\rho_\Delta| \gg |\rho_s|$. As far as this assumption is valid, the apparent r' value of 0.63 in Eq. 3 should not significantly differ from the intrinsic r value for the k_Δ process. Thus the present k_Δ correlation will permit quantitative discussion concerning the substituent effect on the k_Δ quantity as well as on the solvolytic aryl-assisted rate.

The aryl-assisted process of this solvolysis involves significant return from the intermediate, so that the apparent rate constant for this pathway is given as Fk_Δ using a fractionating factor F.[7–9] On the other hand, the present k_Δ quantity based on the product rearrangement is only concerned with the process by which the reactant experiences at least once a symmetrical phenonium intermediate, if any, along the aryl-assisted pathway. It should be emphasized that the k_Δ refers to the relative rate of formation of the first symmetrical intermediate and should be absolutely free from return or any subsequent processes. The identity of both r_Δ values derived from the present k_Δ/k_s and previous k_t analyses evidently indicates that the return process does not cause any significant effect on the ρ and r values for the aryl-assisted pathway. There is independent evidence for the F value of this system being essentially unchanged with substituents.[7–9] The observed r_Δ value should therefore be characteristic of the aryl-assisted ionization step for the phenonium ion intermediate.

Our results from the present study strongly argue against the contrary view that the deviation of the r value from unity or zero should be attributed for most cases to the complexity of mechanism.[11,12] This view is based exclusively on the use of σ^+ of constant resonance exaltation, termed as $1.00\Delta\bar{\sigma}_R^+$, for conjugative carbocation reactions. According to this traditional treatment, the substituent effect on k_Δ should be described by σ^+ and the effect on k_s by σ° (or σ),[12] and the overall effect on (k_Δ/k_s) quantity can be given as the difference of both effects. The situation is merely a special case $r_\Delta=1.0$ and $r_s=0.0$ of Eq. 5. While the r and ρ are mathematically indefinite in Eqs. 4 or 5, this specification of r enables us to give an unequivocal dissection. From the requirement, $r'=0.63\pm0.02=\rho_\Delta r_\Delta/(\rho_\Delta-\rho_s)$ and $\rho'=-3.70=\rho_\Delta-\rho_s$, this treatment should lead to a definite solution, $\rho_\Delta=-2.3$ and $\rho_s=1.4$. However, this ρ_s value is in serious disagreement with the ρ_s value of -0.19 derived from the k_t dissection. Use of σ (i.e., $r=0.27$) instead of σ° results in an even higher ρ_s value of 1.9. The ρ_s is not negative nor much lower than ρ_Δ in the absolute value when σ^+ is used for $\bar{\sigma}_\Delta$. If the k_s process has such a high, positive ρ_s value, the k_t substituent effect will have to exhibit a curved Hammett plot of significant V shape, which is evidently not the case in the present reaction. While the specification of r values, either 0 or 1, greatly simplifies the way of analysis for any complicated systems apparently satisfying Eq. 1, its definite dissection may not be a reasonable one but often an artifact of the treatment. This obvious conflict invalidates the traditional assumption of a constant resonance demand of $r=1$ generally for electrophilic resonance-exalted processes.

Experimental

Material. Deuterated Compounds. Substituted 2-phenylethan-1,1-d_2-ols were prepared in the usual manner from the corresponding substituted phenylacetic acids by reduction with $LiAlD_4$ (99%D) in ether and were converted into the *p*-toluenesulfonates using the Tipson procedure,[16] followed by recrystallization from appropriate solvents. Physical constants of the deuterated derivatives were generally identical with those of their protio derivatives.

Glacial Acetic Acid. Special grade acetic acid was distilled through a 40 cm glass helixes-packed column and a constant boiling fraction of 0.5 °C range (bp 117—117.5 °C) was collected.

Sodium acetate (special reagent grade) was dried on heating in vacuo immediately before use.

Acetolysis. Acetic acid solution 0.02 mol dm^{-3} of 2-arylethyl-1,1-d_2 tosylates in the absence or the presence of NaOAc (0.06 mol dm^{-3}) were allowed to react for more than 10 half-lives in sealed tubes at 115±0.02 °C. The reaction mixture was concentrated under vacuum at room temperature and extracted with chloroform. The extract was treated with cold water and dil. $NaHCO_3$ solution, and dried over anhydrous magnesium sulfate. The chloroform was removed in vacuo at room temperature and the residue was dissolved in carbon tetrachloride or deuteriochloroform to an appropriate concentration of ca. 1 mol dm^{-3} and was subjected to NMR determination.

Proton NMR Measurement. The ^{1}H NMR spectrum was obtained at 90 MHz using a Hitachi Perkin-Elmer R-22 Spectrometer. The accumulation method in CW mode was devised to share the data points most effectively into two peak areas of methylene ($\delta \approx 3$ ppm and ≈ 4 ppm) using a Hitac 10 II computer; only two narrow peak areas of the spectrum were accumulated for 100 times or more, sharing 4000 data points for each peak area (sweep width 40 Hz) of α and β-CH_2 signals. These spectral data were further reconfirmed using Brucker AM 360 Spectrometer which was interfaced with an ASPECT 2000 computer (operating at 360.13 MHz, digital resolution of 0.03 Hz/point).

The % rearrangement was calculated as

$$\frac{100\times[\mathrm{ArCD_2CH_2OAc}]}{[\mathrm{ArCH_2CD_2OAc}]+[\mathrm{ArCD_2CH_2OAc}]}$$

from relative peak intensities of α- and β-methylene protons. The NMR intensity determination was repeated more than three times for each run. The reproducibility of % rearrangement value was generally within ±0.3; the *m*-chloro and 4-MeS-3-CN derivatives showed slightly larger deviation of ±0.5. Average % rearrangement values are given in Table 1. In the NMR analysis, any characteristic peak of solvolysis product other than acetate was not detected, especially in the olefin region, for all derivatives.

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