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RATES OF ADDITION AND DEPROTONATION IN REACTIONS OF FERROCENYLALKYLIUM IONS WITH NUCLEOPHILES

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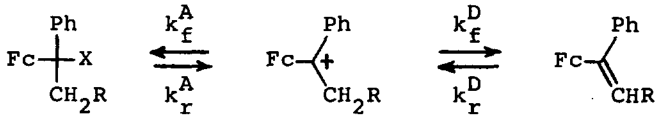
Although nucleophilic addition to isolated carbocations can be studied using triarylmethyl and tropylium cations,[1] no such system is available for deprotonation reactions. However, a range of ferrocenylalkylium ions $Fc\overset{+}{C}R^1R^2$ (R^1,R^2 = H, alkyl, aryl, and Fc) can be obtained as isolable salts and we recently reported[2] results for addition of water to non-deprotonatable systems. We now describe kinetics of addition and deprotonation.



(1) (2) (3)

a; R = H
b; R = CMe(Ph)Fc
c; R = CMe_3
d; R = Ph
e; R = CPh_3

We could not use the methyl-substituted cation (2a) because, during its preparation by acid heterolysis of the alcohol (1a; X = OH) and probably also during solvolysis, deprotonation gave the highly nucleophilic alkene (3a) which rapidly captured (2a) generating the much less reactive "dimeric" cation (2b).* However, there is no coupling for systems incorporating a β-substituent (2; R ≠ H) and we have studied reactions of the neopentyl- (2c), benzyl- (2d), and tritylmethyl- (2e) substituted cations. Their (BF_4^-) salts were obtained by reactions of the alcohols (1c and 1d; X = OH) in acetic anhydride with aq. HBF_4 and by addition of (Ph_3C^+)(BF_4^-) to the alkene (3a).

Addition of (2c)(BF_4^-) to H_2O:MeCN (1:1 w/w) led to first-order disappearance of the cation and formation of a mixture of the alcohol (1c; X = OH) and a single stereoisomer of the alkene (3c). The alkene/alcohol ratio was determined

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* Some pK_{R^+} values determined earlier for $Fc\overset{+}{C}RMe$ may be in error because this cation + alkene coupling was neglected.

both spectroscopically (u.v.) and by product isolation (Al_2O_3 chromatography). Independent experiments showed that the HBF_4 formed in low concentration during solvolysis does not interconvert the products. The rate constants for addition (k_f^A) and deprotonation (k_f^D) were calculated from the observed first-order rate constant for cation disappearance (irreversible product formation) and the kinetic product ratio k_f^D/k_f^A. Similar kinetic and product-ratio studies were carried out for reactions of the same salt with D_2O:MeCN and with MeOH, of (2d) (BF_4^-) with H_2O:MeCN, and of (2e)(BF_4^-) with H_2O:MeCN and with MeOH; the rate constants are in Table 1. In all reactions of the tritylmethyl-substituted cation (2e), a single stereoisomer of the alkene (3e) was the sole product. Reaction of the benzyl analogue (2d) gave the alcohol (1d; X = OH) and both stereoisomers of the alkene (3d), one largely predominating.

Reactions of (2c)(BF_4^-) and (2e)(BF_4^-) with hydroxide (in H_2O:MeCN) and methoxide ion (in MeOH) were also followed and the deprotonation/addition product ratios were determined as before; again, (2e) gave only deprotonation. The rate constants for deprotonation and addition were corrected for the contribution of reaction with solvent. Selected values are: for cation (2c) with 0.10M NaOH in H_2O:MeCN $k_f^D = 2.3\ M^{-1}s^{-1}$ and $k_f^A = 0.17\ M^{-1}s^{-1}$ and with 0.003M NaOMe in MeOH $k_f^D = 78\ M^{-1}s^{-1}$ and $k_f^A = 92\ M^{-1}s^{-1}$; for cation (2e) $k_f^D = 0.82$ and $18.2\ M^{-1}s^{-1}$ with 0.10M NaOH in H_2O:MeCN and 0.003M NaOMe in MeOH respectively.

Reactions of the alcohols (1c and 1d; X = OH) and the related alkenes (3c and 3d) in aqueous acid were also investigated. Addition of (1c; X = OH) to H_2SO_4:H_2O:MeCN gave relatively fast formation of the cation (2c) which slowly underwent deprotonation. In 0.1-1.0M H_2SO_4, heterolysis of the alcohol was essentially complete before the cation was significantly deprotonated. Thus, since $k_f^D \ll k_r^A[H^+] \gg k_f^A$, the observed first-order rate constant for cation build-up gives $k_r^A[H^+]$ for a particular acid concentration. These values are in Table 2. Solutions of (1d; X = OH) in H_2SO_4:H_2O:MeCN showed different kinetic behaviour. For acid strengths in the range 0.1-0.5M, deprotonation of the cation (2d) was much faster than its production by heterolysis of the alcohol. In 0.1M acid, $k_f^D \gg k_r^A[H^+]$ and (2d) does not build up during the reaction. Under these conditions, the observed first-order rate constant for formation of the alkene (3d) from the alcohol (1d; X = OH) is $k_f^D k_r^A[H^+]/(k_f^D + k_f^A)$. Assuming that the k_f^D/k_f^A kinetic product ratio, determined earlier for the collapse of (2d)(BF_4^-) in H_2O:MeCN, is unaffected by 0.1M H_2SO_4, $k_r^A[H^+]$ can thereby be calculated (Table 2).

Addition of either the salt (2c)(BF_4^-) or the alkene (3c) to H_2O:MeCN containing H_2SO_4 ($\geqslant$0.5M) gave equilibrium mixtures of (2c) and (3c) whose compositions were determined spectroscopically. Since $k_r^A[H^+] \gg k_f^A$ at these acid strengths, there is very little alcohol (1c; X = OH) in these mixtures. From the $[R^+]_{eq}/[ene]_{eq}$ values (e.g. 0.12 in 0.50M H_2SO_4 and 7.0 in 2.0M H_2SO_4) and the observed first-order rate constants (k_ψ) for attainment of equilibrium, the k_f^D and $k_r^D[H^+]$ values for given acid concentrations were calculated (Table 2) from the expression:

Table 1. Rate Constants for Deprotonation and Addition Reactions[a]

Cation	Solvent[b]	Nucleophile	k_f^D/k_f^A	k_f^D, s^{-1}	k_f^A, s^{-1}
(2c)	H_2O:MeCN	H_2O	5.67	7.3×10^{-4}	1.3×10^{-4}
	D_2O:MeCN	D_2O	5.25	5.6×10^{-4}	1.1×10^{-4}
	MeOH	MeOH	>20	1.7×10^{-2}	$< 9 \times 10^{-4}$
(2d)	H_2O:MeCN	H_2O	0.50	0.13	0.26
(2e)	H_2O:MeCN	H_2O	∞	8.1×10^{-4}	~ 0
	MeOH	MeOH	∞	6.1×10^{-3}	~ 0

Table 2. Rate Constants for Cation Formation in H_2SO_4:H_2O:MeCN[a,b]

Cation	$[H_2SO_4]$, M	$k_r^A[H^+]$, s^{-1}	$k_r^D[H^+]$, s^{-1}	k_f^D, s^{-1}
(2c)	0	-	-	7.3×10^{-4}
	0.10	2.0×10^{-2}	-	6.8×10^{-4}
	0.25	4.8×10^{-2}	-	5.3×10^{-4}
	0.50	0.12	5.3×10^{-5}	4.3×10^{-4}
	1.00	-	1.5×10^{-4}	3.1×10^{-4}
(2d)	0	-	-	0.13
	0.10	9.6×10^{-3}	c	-
	1.00	-	c	-

[a] Measured at 25.0°C using a Gilford spectrophotometer. [b] H_2O:MeCN (1:1 w/w); D_2O:MeCN (1.1:1 w/w). [c] No alkene protonation detected.

$$k_f^D = k_\psi - k_r^D[H^+] = k_\psi/(1 + [R^+]_{eq}/[ene]_{eq}).$$

The alkene (3d), on the other hand, was extremely resistant to protonation except in highly acidic media. In 4.0M H_2SO_4 in H_2O:MeCN, first-order conversion ($k_\psi = 9.3 \times 10^{-3}\ s^{-1} = k_f^D + k_r^D[H^+]$) to an equilibrium mixture of (2d) and (3d) occurred. However, the equilibrium composition could not be estimated accurately and k_ψ was not separated into forward and reverse rate constants.

The following conclusions can be drawn. The rate constant for addition of water to the benzyl-substituted cation (2d) is similar to those found earlier [2] for similar reactions of non-deprotonatable ferrocenylalkylium ions (e.g. for

$Fc\overset{+}{C}PhCMe_3$, $k_f^A = 0.58\ s^{-1}$). The cation (2c), however, adds water (in H_2O:MeCN) at a rate ca. 2000 times smaller than that for the benzyl analogue and addition to the cation (2e) is completely suppressed. Because nucleophiles add preferentially from the exo-side of the fulvene ligand of ferrocenylalkylium ions,[3] probably via an early carbocation-like transition state,[2] the unreactivity of (2c) and (2e) must reflect steric hindrance to nucleophilic addition by the bulky β-t-butyl and -trityl groups. Additions to ferrocenylvinyl cations ($Fc\overset{+}{C}=CHCMe_3$) are similarly retarded by the β-t-butyl group.[4] The rate constants for addition of methanol, hydroxide, and methoxide ion to (2c) suggest that these reactions are also sterically retarded. The kinetic solvent isotope effect for addition of $H_2O(D_2O)$ to (2c) ($k_f^{H_2O}/k_f^{D_2O} = 1.2$) is similar to those for non-deprotonatable carbocations (e.g. tri-p-anisylmethyl cation[5] and ferrocenylalkylium ions[2]).

The cations (2c) and (2e) eliminate to the corresponding alkenes very much more slowly than the benzyl-substituted cation (2d) where the β-phenyl group is conjugated with the developing double bond. Steric effects also appear to be important in these reactions as suggested by the kinetically-controlled formation of a single alkene stereoisomer on deprotonation of (2c) and (2e); elimination from (2d) gives predominantly ($\gg$90%) one alkene stereoisomer. We are investigating this aspect further but, assuming that deprotonation as well as addition is from the exo-direction, consideration of the ground-state conformation of the system suggests that cations of the type (2) should give preferentially the alkene stereoisomer in which the Fc and R groups are trans. Proton transfer from (2c) to D_2O is slightly slower than to H_2O ($k_f^{H_2O}/k_f^{D_2O} = 1.3$) and, as expected, deprotonation of (2c) in H_2SO_4:H_2O:MeCN is retarded as the acidity increases; deprotonation is also slowed in the presence of salts (e.g. $NaClO_4$, NaOTs).

The ferrocenylalkylium system allows for the first time a comparison of nucleophilic addition and elimination reactions of pre-formed carbocations rather than of cations or, more probably, ion pairs formed in S_N1 reactions.

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