Kinetics and mechanism of nucleophilic displacements with heterocycles as leaving groups. Part 23.[1] Studies at the borderlines between reactions proceeding (*i*) via free carbocations, (*ii*) via rate-determining formation of ion–molecule pairs, and (*iii*) via rate-determining nucleophilic attack on ion–molecule pairs

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This paper is dedicated to Professor Arthur N. Bourns

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Evidence is presented to demonstrate that at the borderline between first-order reaction via nucleophilic trapping of intimate ion–molecule pairs and first-order reaction via the formation of free carbocations, both mechanisms proceed independently, without merging. Similarly at the borderline between first-order (rate-determining formation) and second-order (rate-determining nucleophilic attack) reactions of intimate ion–molecule pairs, both reactions again proceed independently.

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On présente des données qui démontrent que, à la limite entre la réaction du premier ordre se produisant par le piégeage nucléophile de paires intimes ion–molécule et la réaction du premier ordre se produisant par le biais de la formation de carbocations libres, les deux mécanismes se produisent d'une façon indépendante, sans se confondre. De la même manière, à la limite entre les réactions du premier ordre (la formation est l'étape déterminante) et du deuxième ordre (l'attaque nucléophile est l'étape déterminante) des paires intimes ion–molécule, chacune des réactions se produit encore une fois d'une façon indépendante.

[Traduit par la revue]

Introduction

Nucleophilic displacements of the N-substituents in pyridinium cations have been shown to proceed by each of the five mechanisms of Scheme 1 (1). In solvents of low nucleophilicity solvolyses of *N*-(primary alkyl)pyridiniums occur via ion-pair intermediates formed without anchimeric assistance by synchronous rate-enhancing H^+ or R^+ migration (2). Nucleophilic displacement of *N*-(secondary alkyl)pyridiniums can occur by the classical S_N2 reaction, by rate-determining ion-pair formation, or by rate-determining ion-pair dissociation, depending on the conditions (3). In particular, no evidence was found in these systems for any "merging" of S_N1–S_N2 reaction type or for the "S_N2 intermediate" mechanism which has been advocated by Bentley and Schleyer (4). We have recently confirmed that the nature of the gegen ion, or the presence of small quantities of water, have no significant effect on the rate.[3]

Studies of tertiary alkyl halides and sulfonates have usually been interpreted to demonstrate that nucleophilic displacement occurs exclusively by unimolecular S_N1 type mechanism: with (5) or without (6) the intermediacy of ion-pairs. Although Bentley and co-workers have recently advocated nucleophilic solvent assistance in the solvolysis reactions of such *t*-alkyl substrates (7, 8) our own detailed studies of *N*-(*t*-alkyl)pyridinium salts[4] have shown solvolysis rates almost independent of solvent, and with less variation with the substrate structure than found for analogs with anionic leaving groups: specifically, no evidence was found for nucleophilic assistance by solvent.

The use of positively charged substrates and neutral leaving groups has several advantages for the study of nucleophilic substitution mechanisms (1). Unimolecular reactions of a neutral substrate involve charge creation: such reactions require media of high dielectric constant, where the role of the medium as solvent and as nucleophile is not easily disentangled. Substrates with neutral leaving groups can undergo unimolecular reactions in media of low dielectric constant. Furthermore, the reaction scheme is less complex in that the distinction (caused by strong electrostatic attraction) between a solvent-separated ion pair and a free carbocation disappears: for positively charged substrates we simply have intimate ion–molecular pairs and free carbocations.

To better understand the detailed mechanism of nucleophilic substitution at sp^3-hybridised carbon atoms, we wished to investigate four mechanistic borderlines utilizing pyridines as leaving groups (Scheme 1). These borderlines comprise: (*1*) that between first-order reactions involving ion-molecule pairs and first-order reactions proceeding via dissociation into free carbocations; (*2*) that between first-order and second-order reactions of nucleophiles with ion–molecule pairs; (*3*) that between second-order attack on ion–molecule pairs and second-order mechanism proceeding by direct displacement; (*4*) that between classical second-order displacements and second-order displacements involving previous electron transfer.

The present paper describes the results of investigations aimed at the further clarification of borderlines (*1*) and (*2*). In particular, we wished to investigate whether it was possible to explain the results at the borderlines by the simultaneous operation of the two appropriate independent reaction mechanisms, or whether "merging" occurred between them so that a reaction occurred by a single mechanism of intermediate type. In other words, do the two mechanisms remain distinct and competitive with dominance passing gradually from one to the other or does a single mechanism always operate with gradual change over?[5]

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[5]Opposing views on this general and fundamental question complicate the teaching of this subject, see ref. 19.

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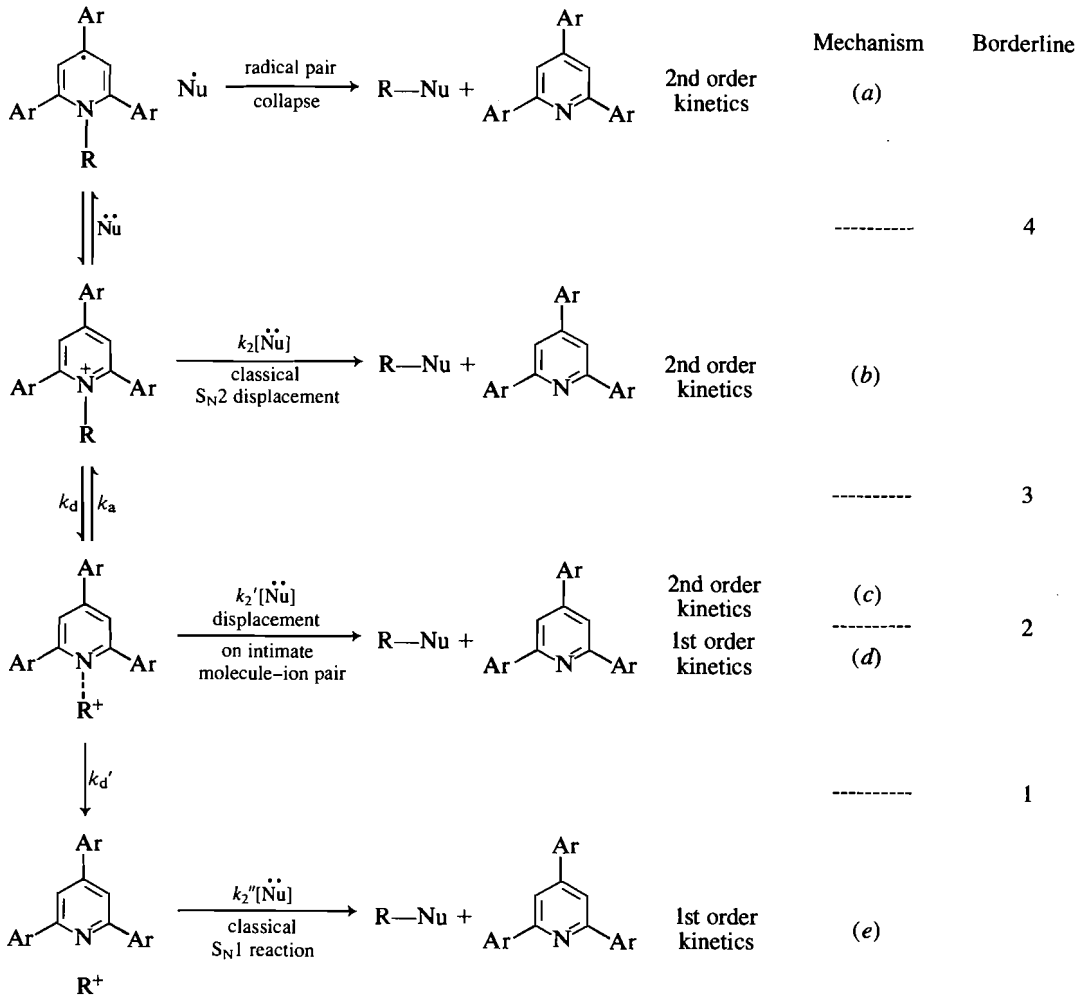


SCHEME 1. Nucleophilic substitutions with pyridine-leaving group

Borderline (*1*) between classical S_N1 and S_N1 by nucleophilic capture of an ion–molecule pair

In the region of this borderline, competition between two alternative first-order reactions occurs: (*i*) mechanism *d*; capture by solvent or nucleophile at the ion–molecule pair stage (i.e. rate-determining formation of the ion–molecule pair) and (*ii*) mechanism *e*; dissociation of the ion–molecule pair to give a free carbocation followed by further reactions with solvent or nucleophile (here the rate-determining step could be either formation of a ion–molecule pair or its dissociation to a carbocation).

Some results for solvolyses of secondary alkyl substrates indicating that reaction can occur either via free carbocations or via solvent capture of an ion–molecule pair (the first borderline region) have already been reported (3). The present experiments were based on the expectation that secondary substrates in non- or very weakly nucleophilic solvents with small amounts of strong nucleophiles (piperidine or morpholine) should give first-order kinetics (no dependence of nucleophile concentration) but undergo reaction via ion–molecule pairs, i.e. without any rearrangement of the secondary substrates. By contrast, weak nucleophiles such as 1,1,1,3,3,3-hexafluoropropan-2-ol or trifluoroacetic acid should give classical unimolecular reaction via free carbocations, and carbocation rearrangements should occur.

Solvolyses[6] of 1-(2-pentyl)-5,6-dihydro-2,4-diphenylbenzo[*h*]quinolinium trifluoromethanesulphonate (**2***c*) and 1-(3-pentyl)-5,6-dihydro-2,4-diphenylbenzo[*h*]quinolinium tetrafluoroborate (**2***e*) in chlorobenzene occur at convenient rates at 65.0°C. The kinetics of these solvolyses were followed spectrophotometrically at 345 nm. In pure, unbuffered solvent an initial decrease in absorption followed by an increase is due to acid–base equilibria (cf. footnote 4). These equilibria were suppressed *either* by carrying out the reaction in the presence of triethylamine, *or* by diluting the kinetic solutions with chlorobenzene containing trifluoroacetic acid prior to measurement of the absorbance. With this precaution, all reactions showed good pseudo-first-order behaviour. Reactions carried out in the presence of a nucleophile (piperidine, morpholine, pyridine, lutidine, anisole, *p*-chlorophenol, acetic acid, or trifluoroacetic acid) were measured under pseudo-first-order conditions: good straight lines were obtained to at least 70% completion. The observed rate constants (k_{obs}) (Tables 1 and 2) plotted against

[6]Here and elsewhere the word "solvolysis" is used to denote a reaction which is induced by the fact that a substrate is dissolved in a solvent. In a solvolysis, a solvent molecule need not be involved in the rate-determining stage. Solvolyses of some of the present and other similar substrates, in the absence of added nucleophiles has been shown to give various products of carbocation attack on solvent or product molecules (unpublished work) when elimination is not possible.

TABLE 1. Pseudo-first-order rate constants for the reactions of 1-(2-pentyl)-5,6-dihydro-2,4-diphenylbenzo[*h*]quinolinium trifluoromethanesulphonate **2***c* with nucleophiles in chlorobenzene at 65.0°C[a]

Entry No.	Nucleophile (mol L^{-1})	$10^5 k_{obs}$ (s^{-1})	Error (%)	*r*	React. (%)
1	None	18.75 ± 0.19	1.00	0.9998	86.8
	Piperidine				
2	0.0005[b]	18.94 ± 0.08	0.44	0.99998	81.8
3	0.0010[b]	18.96 ± 0.07	0.38	0.99998	81.8
4	0.0100[b]	19.12 ± 0.11	0.56	0.99997	82.2
5	0.1000[b]	22.51 ± 0.09	0.38	0.99998	80.3
6	1.000[b]	50.29 ± 0.23	0.45	0.99997	85.8
	Morpholine				
7	0.005	16.85 ± 0.15	0.92	0.99985	78.1
8	0.010	17.33 ± 0.21	1.19	0.99975	79.0
9	0.050	17.87 ± 0.52	0.52	0.99995	80.0
10	0.100	18.65 ± 0.16	0.85	0.99987	81.5
11	0.200	19.36 ± 0.11	0.55	0.99995	82.5
12	0.400	22.25 ± 0.21	0.96	0.99984	86.5
13	0.600	27.25 ± 0.37	1.35	0.99968	91.5
	Pyridine				
14	0.005	18.62 ± 0.04	0.23	0.99999	81.3
15	0.010	18.75 ± 0.06	0.31	0.99998	81.5
16	0.050	18.50 ± 0.07	0.36	0.99998	81.5
17	0.100	18.57 ± 0.09	0.46	0.99996	81.0
18	0.200	18.67 ± 0.11	0.60	0.99994	81.4
19	0.400	18.65 ± 0.11	0.61	0.99993	81.3
	2,6-Lutidine				
20	0.001	18.78 ± 0.10	0.52	0.99997	78.1
21	0.010	18.84 ± 0.23	1.26	0.99982	81.7
22	0.050	18.98 ± 0.09	0.47	0.99997	81.9
23	0.100	18.86 ± 0.10	0.52	0.99997	81.7
24	0.400	19.01 ± 0.15	0.81	0.99993	81.9
	Isopropylamine				
25	0.005	17.97 ± 0.10	0.57	0.99994	80.1
26	0.010	18.37 ± 0.12	0.66	0.99993	80.8
27	0.050	19.53 ± 0.27	0.27	0.99999	82.7
28	0.100	19.89 ± 0.18	0.93	0.99987	78.7
29	0.400	25.50 ± 0.32	1.26	0.99982	78.7
30	1.000	31.32 ± 0.94	2.99	0.9984	76.3
	p-*Chlorophenol*				
31	0.001[c]	18.89 ± 0.96	5.10	0.9989	78.5
32	0.050[c]	18.78 ± 0.93	4.95	0.9990	77.6
33	0.010[c]	18.76 ± 0.92	4.80	0.9990	76.5
34	0.100[c]	18.81 ± 0.88	4.68	0.9991	75.2
35	1.000[c]	18.93 ± 1.00	5.28	0.9989	76.9
	Anisole				
36	0.001[d]	18.90 ± 0.09	0.47	0.9999	81.7
37	0.010[d]	19.30 ± 0.15	0.78	0.9999	82.2
38	0.100[d]	18.84 ± 0.09	0.50	0.9999	81.7
39	1.000[d]	18.94 ± 0.12	0.62	0.9999	81.9
	Acetic acid				
40	0.1[e]	18.07 ± 0.93	5.15	0.9987	66.3
41	1.0[e]	18.18 ± 0.96	5.24	0.9986	66.3
	Trifluoroacetic acid				
42	0.1[e]	17.95 ± 1.40	7.78	0.9970	65.7
43	1.0[e]	17.49 ± 1.15	6.57	0.9978	64.0

[a]Concentration of pyridinium salt 2.8×10^{-5} (mol L^{-1}); measured at 345 nm.
[b]Concentration of pyridinium salt 1×10^{-4} (mol L^{-1}); measured at 345 nm.
[c]Kinetic solutions of the pyridinium salt (2.8×10^{-5} mol L^{-1}) were diluted to uv concentration (1.4×10^{-5} mol L^{-1}) using 8% (v/v) solution of trifluoroacetic acid in chlorobenzene; measured at 360 nm.
[d]Solvent contained triethylamine, 2.8×10^{-4} (mol L^{-1}).
[e]Kinetic solutions of the pyridinium salt (1.4×10^{-4} mol L^{-1}) were diluted to uv concentration (2.8×10^{-5} mol L^{-1}) using 5% (v/v) solution of triethylamine in chlorobenzene; measured at 345 nm.

TABLE 2. Pseudo-first-order rate constants for the reactions of 1-(3-pentyl)-5,6-dihydro-2,4-diphenylbenzo[*h*]quinolinium tetrafluoroborate **2***e* with nucleophiles in chlorobenzene at 65.0°C[a]

Entry No.	Nucleophile (mol L^{-1})	$10^5 k_{obs}$ (s^{-1})	Error (%)	*r*	React. (%)
1	None	15.93 ± 0.09	0.61	0.9999	86.1
	Morpholine				
2	0.001	16.03 ± 0.15	0.95	0.9999	79.6
3	0.010	16.49 ± 0.15	0.91	0.9999	80.6
4	0.100	17.63 ± 0.31	1.76	0.9994	81.7
5	1.000	29.02 ± 0.58	2.00	0.9995	82.7
	Pyridine				
6	0.001	16.26 ± 0.06	0.38	0.99997	76.9
7	0.010	16.31 ± 0.09	0.55	0.99995	77.0
8	0.100	16.38 ± 0.03	0.16	0.99999	77.1
9	0.500	16.51 ± 0.05	0.29	0.99999	77.4
	2,6-Lutidine				
10	0.001	15.59 ± 0.11	0.74	0.9999	81.5
11	0.010	15.75 ± 0.13	0.83	0.9999	81.9
12	0.100	16.31 ± 0.11	0.69	0.9999	81.0
13	1.000	16.82 ± 0.09	0.55	0.9999	80.1
	Anisole				
14	0.001[b]	18.72 ± 0.08	0.43	0.9999	79.1
15	0.010[b]	18.51 ± 0.11	0.62	0.9999	78.9
16	0.100[b]	19.54 ± 0.14	0.71	0.9999	80.5
17	1.000[b]	20.93 ± 0.12	0.57	0.9999	80.4
	Acetic acid				
18	0.1[c]	16.52 ± 0.82	4.98	0.9988	61.9
19	1.0[c]	16.68 ± 1.09	6.51	0.9979	62.7
	Trifluoroacetic acid				
20	0.1[c]	17.67 ± 0.87	4.91	0.9988	65.3
21	1.0[c]	16.86 ± 1.47	8.72	0.9962	62.5

[a]Concentration of pyridinium salt 2.8×10^{-5} (mol L^{-1}); measured at 345 nm.
[b]Solvent contained triethylamine, 2.8×10^{-4} (mol L^{-1}).
[c]Kinetic solutions of pyridinium salt (1.4×10^{-4} mol L^{-1}) were diluted to uv concentration (2.8×10^{-5} mol L^{-1}) using 5% (v/v) solution of triethylamine in chlorobenzene; measured at 345 nm.

concentration of nucleophile gave straight lines (Figs. 1 and 2). The derived first order rate constants (intercepts) are given in Table 3. Weak nucleophiles such as *p*-chlorophenol, anisole, or acetic acid have negligible effects on the rate: strong nucleophiles (piperidine, morpholine) show only small rate accelerations, i.e. first-order predominates over second-order reaction. Similar results were previously obtained (3*b*) for the solvolyses of a series of 1-(s-alkyl)pyridinium cations in $CHCl_3$, CH_3CN, TFE, and $(CF_3)_2CHOH$ as solvents, and with pyridine, piperidine, or morpholine as added nucleophiles.

Product analyses were carried out by gc/ms. The solvolysis of 2-pentyl derivative **2***c*, in chlorobenzene at 65°C containing morpholine (0.1 *M*) (i.e. under conditions where over 91% of the reaction is kinetically of first-order) gave: pentene (14%) and *N*-2-pentylmorpholine (86%) (Table 7).[7] The mass spectrum of pentene shows three peaks at *m/z* 70 (M^+), 55 ($C_4H_7^+$, the base peak), and 42 ($C_3H_6^+$), the two latter correspond to $M^+ - CH_3$ and to $M^+ - CH_2{=}CH_2$, respectively (9), and clearly show the pent-2-ene structure (10). *N*-2-Pentylmorpholine shows three major peaks at *m/z* 157, 142, and 114 which correspond to molecular ion, to $M^+ - CH_3$, and to $M^+ - C_3H_7$, respectively (Table 7). In tertiary amines, loss of the largest branch from the α-C atom is preferred. Since the peak at *m/z* 114 is the base peak, the fragmentation pattern corresponds to the *N*-(2-pentyl)morpholine structure. Thus, the solvolysis of **2***c* in chlorobenzene in the presence of morpholine gave mixtures of pent-2-ene (14.4 ± 2.0%; elimination product) and *N*-2-pentylmorpholine (85.6 ± 2.0%; nonrearrangement product): specifically no *N*-3-pentylmorpholine could be detected. Similarly, solvolysis of **2***c* in the presence of acetic acid (1 *M*) gave only 2-pentyl acetate, the fragmentation pattern of which exhibited a characteristic fragment ion at *m/z* 87 corresponding to $M^+ - 43$. No peak at *m/z* 101 for 3-pentyl acetate (rearranged product) was found.

Gas chromatography/mass spectral analysis of the products from solvolyses of the 2-pentyl derivative **2***c* in chlorobenzene in the presence of *p*-chlorophenol gave pent-2-ene (72.7%) and *p*-chlorophenyl-2-pentyl ether (27.3%) which showed five significant peaks (Table 9). The structure of the ether is supported by the base peak at *m/z* 128 and the peak at *m/z* 111 corresponding respectively to cleavage β and α to the ring, with hydrogen migration. β-Cleavage of aromatic ethers is dominant; therefore the peak at *m/z* 128 is the base peak. The peaks at *m/z* 155 ($M^+ - 43$) and *m/z* 43 ($C_3H_7^+$) prove the 2-pentyl structure. Solvolysis of 2-pentyl derivative **2***c* in chlorobenzene in the presence of anisole gave only pent-2-ene.

The fact that the rate constants, and specifically the inter-

[7]Tables 7 to 9 have been deposited. Complete set of material may be obtained, at a nominal charge, from the Depository of Unpublished Data, CISTI, National Research Council of Canada, Ottawa, Ont., Canada K1A 0S2.

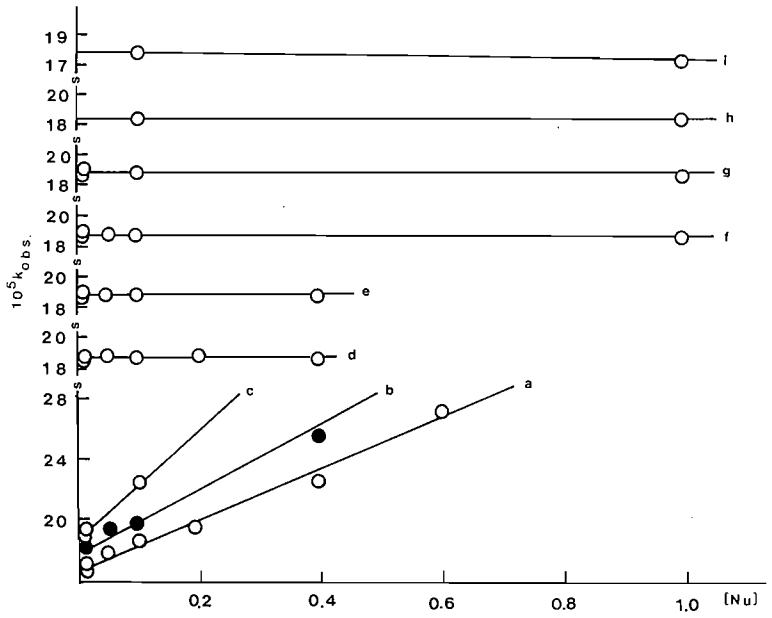


FIG. 1. Plots of observed rate constants for the solvolyses of 1-(2-pentyl)-5,6-dihydro-2,4-diphenylbenzo[*h*]quinolinium trifluoromethanesulphonate **2***c* in chlorobenzene at 65.0°C vs. nucleophilic concentration; *a*, morpholine; *b*, isopropylamine; *c*, piperidine; *d*, pyridine; *e*, 2,6-lutidine; *f*, *p*-chlorophenol; *g*, anisole; *h*, acetic acid; *i*, trifluoroacetic acid.

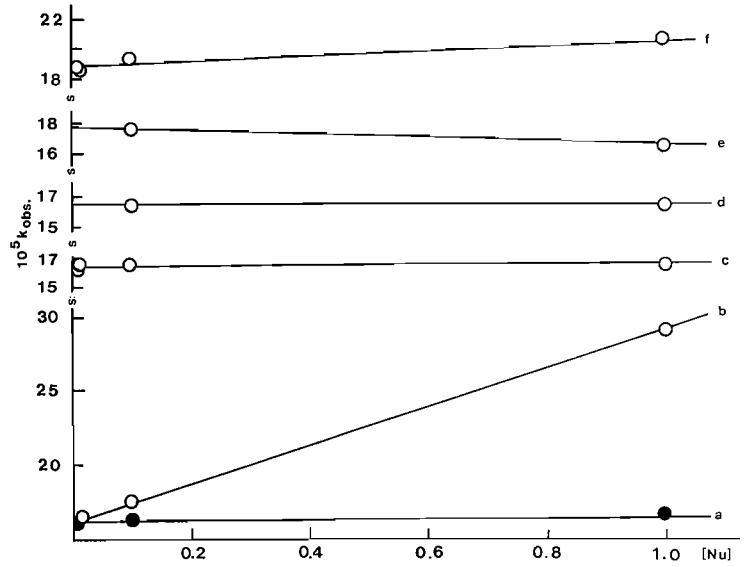


FIG. 2. Plots of observed rate constants for the solvolyses of 1-(3-pentyl)-5,6-dihydro-2,4-diphenylbenzo[*h*]quinolinium tetrafluoroborate **2***e* in chlorobenzene at 65.0°C vs. nucleophilic concentration; *a*, 2,6-lutidine; *b*, morpholine; *c*, pyridine; *d*, acetic acid; *e*, trifluoroacetic acid; *f*, anisole.

cepts, for the reaction of the 2-pentyl derivative **2***c* in chlorobenzene containing morpholine, *p*-chlorophenol, and anisole are so similar, whereas the proportion of elimination varies from 14–100%, confirms that the rate-determining step occurs before elimination.

Solvolysis of 3-pentyl derivative **2***e* in chlorobenzene containing morpholine (0.1 *M*) gave 2-pentene (88%) (identified as above) and *N*-3-pentylmorpholine (12%) (Table 8) for which the only two peaks above *m/z* 100 at *m/z* 157 (1.67%) and *m/z* 128 (100%) correspond to M^+ and to $M^+ - C_2H_5$, respectively, and prove the structure. No *N*-2-pentylmorpholine was detected. Likewise solvolysis of **3***a* in chlorobenzene containing acetic acid gave only the 3-pentyl acetate which showed a fragment ion at *m/z* 101 which corresponds to $M^+ - 29$, and no peak at *m/z* 87 (for rearranged 2-pentyl acetate) was detected.

The kinetic results discussed above show that there is no large rate acceleration in the reactions of **2***c* and **2***e* when 0.1 *M* morpholine or 1 *M* acetic acid is added to chlorobenzene. However, morpholine or acetic acid is able to intercept the incipient 2- or 3-pentyl carbocations before rearrangement to give only the 2-pentyl or only the 3-pentyl products, respectively, which strongly suggests that the solvolyses of **2***c* and **2***e* occur through intimate ion–molecule pairs. This supports the conclusions drawn from our earlier work with 1,1,1,3,3,3-hexafluoropropan-2-ol (3): solvolyses of **2***c* and **2***e* in this solvent gave identical mixtures of rearranged and non-rearranged ether

TABLE 3. First-order (k_1) and second-order (k_2) rate constants for the reactions of 1-substituted pyridinium salts (**2c**, **2e**) with nucleophiles in chlorobenzene

Compound	Nucleophile	N^a	R^b	Slope		Intercept		$10^3 k_1{}^f$
				$10^3 k_2{}^{c,d}$	% Error	$10^5 k_1{}^{d,e}$	% Error	$k_2 + 10k_1$
2c	Piperidine	5	0.9999	0.313 ± 0.009	2.8	19.00 ± 0.40	2.1	85
2c	Morpholine	5	0.9995	0.171 ± 0.01	5.8	16.97 ± 0.27	1.6	>91
2c	Pyridine	6		(0.62 ± 5.3) × 10^{-3}		18.62 ± 0.10	0.5	>99.9
2c	Lutidine	5		(0.43 ± 0.72) × 10^{-3}		18.83 ± 0.13	0.7	>99.9
2c	Isopropylamine	6	0.9872	0.133 ± 0.02	15.2	18.62 ± 0.89	4.8	93
2c	*p*-Chlorophenol	5		(0.12 ± 0.21) × 10^{-2}		18.80 ± 0.09	0.5	>99.9
2c	Anisole	4		(0.963 ± 1.210) × 10^{-3}		19.02 ± 0.09	0.5	>99.9
2c	Acetic acid	2		0.002 ± 0.021		18.05 ± 1.14	6.3	>99.9
2c	Trifluoroacetic acid	2		−0.005 ± 0.028		18.06 ± 1.62	9.0	>99.9
2e	Morpholine	4	0.997	0.13 ± 0.01	7.7	16.24 ± 0.11	0.7	93
2e	Pyridine	4	0.9963	0.004 ± 0.001	25.0	16.30 ± 0.41	2.5	99
2e	Lutidine	4		0.010 ± 0.001	10.0	15.83 ± 1.35	8.5	99
2e	Anisole	4	0.95	0.021 ± 0.004	19.0	18.83 ± 1.23	6.5	99
2e	Acetic acid	2		0.002 ± 0.021		16.50 ± 1.03	6.2	>99.9
2e	Trifluoroacetic acid	2		−0.009 ± 0.026		17.76 ± 1.13	6.3	>99.9

[a]Numbers of runs.
[b]Correlation coefficient.
[c]L mol^{-1} s^{-1}.
[d]90% confidence limit.
[e]s^{-1}.
[f]Percentage reaction by unimolecular route at [nucleophile] 10^{-1} mol L^{-1}.

TABLE 4. Pseudo-first-order rate constants for the reactions of 1-benzyl-5,6,8,9-tetrahydro-7-phenyldibenzo[*c*,*h*]acridinium trifluoromethanesulphonate **3b** with nucleophiles in chlorobenzene[a]

Entry No.	Temperature (°C)	Nucleophile (mol L^{-1})	$10^5 k_{obs}$ (s^{-1})	Error (%)	*r*	React. (%)
1	60	None[b]	3.98 ± 0.09	2.26	0.9996	70.1
		Morpholine				
2	65	0.00005	8.75 ± 0.10	1.16	0.9998	69.7
3	65	0.00010	11.25 ± 0.10	0.92	0.9999	80.5
4	65	0.00050	26.37 ± 0.30	1.15	0.9999	88.3
5	65	0.00100	50.25 ± 0.79	1.57	0.9999	89.7
6	65	0.00500	221.75 ± 2.46	1.11	0.9999	93.0
		Pyridine				
7	65	0.0001	7.44 ± 0.04	0.60	0.9999	73.9
8	65	0.0010	7.69 ± 0.05	0.69	0.9999	75.2
9	65	0.0100	11.47 ± 0.05	0.46	0.9999	74.8
10	65	0.0500	28.80 ± 0.23	0.80	0.9999	79.1
11	65	0.1000	49.74 ± 0.48	0.97	0.9999	83.4
		Pyridine				
12	60	0.0001	4.15 ± 0.03	0.70	0.9999	77.5
13	60	0.0010	4.28 ± 0.05	1.19	0.9999	75.2
14	60	0.0050	5.20 ± 0.08	1.51	0.9998	81.7
15	60	0.0100	6.85 ± 0.20	2.88	0.9998	81.0
16	60	0.0500	17.83 ± 0.05	0.29	1.0000	61.8
		2,6-Lutidine				
17	60	0.0001	4.03 ± 0.04	1.01	0.9999	76.9
18	60	0.0010	4.02 ± 0.03	0.70	0.9999	66.4
19	60	0.0050	4.07 ± 0.02	0.52	0.9999	66.6
20	60	0.0100	4.11 ± 0.02	0.60	0.9999	64.6
21	60	0.0500	4.41 ± 0.04	0.99	0.9998	69.9
		Isopropylamine				
22	60	0.0001	3.99 ± 0.04	1.09	0.9998	88.7
23	60	0.0050	15.01 ± 0.12	0.78	0.9999	88.6
24	60	0.0500	120.84 ± 3.02	2.50	0.9998	88.6

[a]Concentration of pyridinium salt 2.0 × 10^{-5} (mol L^{-1}); measured at 399 nm.
[b]Solvent contained triethylamine, 2.0 × 10^{-4} (mol L^{-1}); measured at 399 nm.

TABLE 5. Pseudo-first-order rate constants for the reactions of 1-(*p*-methoxybenzyl)-2,4,6-triphenylpyridinium tetrafluoroborate **1***b* with anisole in chlorobenzene at 65.0°C[a]

Entry No.	Anisole (mol L^{-1})	$10^5 k_{obs}$ (s^{-1})	Error (%)	*r*	React. (%)
1	0.000[b]	96.49 ± 0.53	0.55	0.99999	90.1
2	0.100[b]	97.10 ± 0.60	0.62	0.99998	87.7
3	0.500[b]	99.46 ± 0.58	0.58	0.99997	87.5
4	1.000[b]	101.71 ± 0.55	0.55	0.99998	88.1

[a]Concentration of pyridinium salt 9×10^{-5} (mol L^{-1}), measured at 312 nm.
[b]Solvent contained triethylamine, 1×10^{-3} (mol L^{-1}).

products, evidently by a carbocation mechanism; however, solvolysis of **2***c* and **2***e* in 1,1,1,3,3,3-hexafluoropropan-2-ol in the presence of morpholine as nucleophile, gave the non-rearranged *N*-(2-pentyl)- and *N*-(3-pentyl)-morpholine products, respectively, just as we have now observed (3*b*).

We showed previously (3*b*) that both the 2-pentyl and the 3-pentyl substrates underwent solvolysis in trifluoroacetic acid to give the same mixture of 2-pentyl and 3-pentyl trifluoroacetates. We have now carried out solvolysis of **2***c* and **2***e* in chlorobenzene in the presence of trifluoroacetic acid (1 *M*): in further confirmation of our previous work, in each case a mixture of *both* the 2-pentyl and 3-pentyl trifluoroacetates was obtained. Although the trifluoroacetates were not separable under gc condition used,[8] the fragmentation pattern of the isomeric mixture obtained from the solvolysis of the 2-pentyl derivative **2***c* on gc/ms analysis exhibited characteristic fragment ions for both *m/z* 155 and 141, which correspond to the rearranged product (3-pentyl trifluoroacetate *m/z* 155, i.e. $M^+ - 29$) and the non-rearranged product (2-pentyl trifluoroacetate *m/z* 141, i.e. $M^+ - 43$, respectively). The same fragmentation pattern was obtained on analysis of the mixture obtained from the 3-pentyl derivative.

Borderline (*2*): reactions by rate-determining formation of an ion–molecule pair and by rate-determining attack by nucleophile

In this region, reactions proceed by capture of an ion–molecule pair by the solvent or added nucleophile, and competition occurs between two different mechanisms: (*i*) mechanism *d* or *e*; rate-determining formation of the ion–molecule pair, or of the free carbocation, i.e. unimolecular reaction mode and (*ii*) mechanism *b* or *c*; rate-determining nucleophilic attack, i.e. bimolecular reaction mode. Here, we have studied the behaviour of the *N*-benzylpentacyclic pyridinium cation in chlorobenzene containing small amounts of nucleophiles, i.e. under conditions where both mechanisms should be of comparable importance.

Solvolyses of 1-benzyl-5,6,8,9-tetrahydro-7-phenyldibenzo[*c*,*h*]acridinium trifluoromethanesulphonate (**3***b*) and 1-(*p*-methoxybenzyl)-2,4,6-triphenylpyridinium tetrafluoroborate **1***b* in chlorobenzene occur at convenient rates at 65.0°C and were followed spectrophotometrically at 399 and 312 nm, respectively. In pure solvent an initial decrease in absorption is followed by an increase due to acid–base equilibria; this was avoided by the addition of small amounts of NEt_3 (see experimental section). Reactions carried out in the presence of morpholine, pyridine, lutidine, isopropylamine, and anisole, measured under pseudo-first-order conditions, gave good straight lines to at least 62% completion. The observed rate constants (k_{obs}) (Tables 4 and 5) for these reactions plotted against concentration of nucleophile gave straight lines (Fig. 3). The first order rate constants (intercepts) are given in Table 6.

[8]Conditions: 3% SP 2100 on 100/120 Supelcoport, flow rate 30 mL/min, helium carrier gas, 40–200 deg at 10 deg/min.

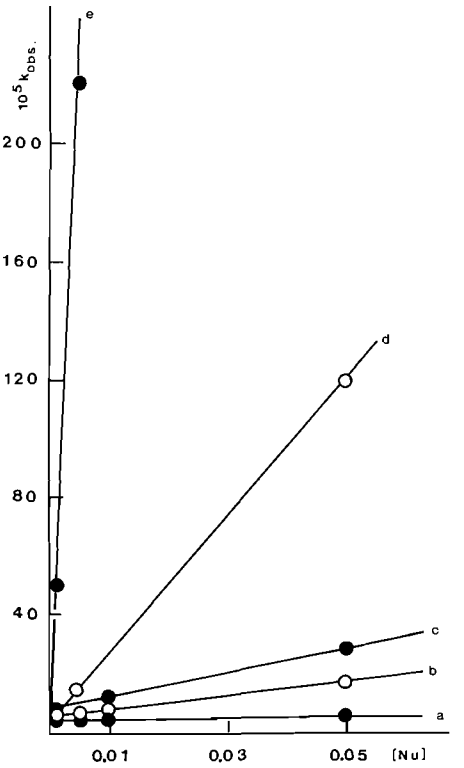


FIG. 3. Plots of observed rate constants for the solvolyses of 1-benzyl-5,6,8,8-tetrahydro-7-phenyldibenzo[*c*,*h*]acridiniumtrifluoromethanesulphonate **3***b* in chlorobenzene vs. nucleophilic concentration; *a*, 2,6-lutidine (60°C); *b*, pyridine (60°C); *c*, pyridine (65.0°C); *d*, isopropylamine (60°C); *e*, morpholine.

The *N*-benzylpentacyclic derivative **3***b* reacts with morpholine almost exclusively via a bimolecular route (Table 6). Dramatically different is the reaction of **3***b* with lutidine; for this much less powerful nucleophile the second-order component is insignificant and the substrate undergoes solvolysis almost entirely via a unimolecular route. For solvolysis in the presence of pyridine, the percentage reaction by the unimolecular route is found to be 15% at 65.0°C and 13% at 60.0°C for 0.1 *M* nucleophile. It has been demonstrated that *N*-benzylpentacyclic derivative **3***b* reacts with piperidine predominantly through the second-order reaction of the intimate ion–molecule pair with the nucleophile at normal and fairly low pressures, but that at higher pressures reaction by the classical S_N2 process takes over (11). We therefore believe that at normal pressures the dominant second-order reaction of **3***b* with morpholine is also via the intimate ion–molecule pair. The first-order rates at 65°C for the *N*-benzylpentacyclic derivative **3***b* do not change appreciably on changing the nucleophile: morpholine $6.38 \times 10^{-2}\ s^{-1}$, pyridine $7.33 \times 10^{-5}\ s^{-1}$. Similarly, first-order rates for **3***b* at 60°C are likewise constant: pyridine $4.01 \times 10^{-5}\ s^{-1}$, lutidine $4.03 \times 10^{-5}\ s^{-1}$, isopropylamine $3.53 \times 10^{-5}\ s^{-1}$. The solvolysis rate of **3***b* in the absence of nucleophile is $(3.98 \pm 0.09) \times 10^{-5}\ s^{-1}$ at 60.0°C. We interpret this invariance as evidence that there is no merging of the unimolecular (S_N1 type) and bimolecular (S_N2 type) mechanisms; rather two mechanisms can and do proceed independently. If the bimolecular mode is the reaction of nucleophile with the ion–molecular

TABLE 6. First-order (k_1) and second-order (k_2) rate constants for the reactions of 1-substituted pyridinium salts with nucleophiles in chlorobenzene

Compound	Nucleophile	Temperature (°C)	N^a	R^b	Slope		Intercept		$10^3 k_1{}^f$
					$10^3 k2^{c,d}$	% Error	$10^5 k_1{}^{d,e}$	% Error	$k_2 + 10k_1$
1*b*	Anisole	65	3	0.997	0.05 ± 0.01	20.0	96.70 ± 0.99	1.0	>99
3*b*	Pyridine	65	5	0.9999	4.25 ± 0.06	1.3	7.33 ± 0.29	3.9	15
3*b*	Pyridine	60	5	0.9998	2.76 ± 0.10	3.6	4.01 ± 0.22	5.7	13
3*b*	Lutidine	60	5	0.9986	0.077 ± 0.07	9.3	4.03 ± 0.02	0.5	>99
3*b*	*i*-$PrNH_2$	60	3	1.000	23.40 ± 0.06	0.3	3.53 ± 0.01	0.3	<1
3*b*	Morpholine	65	5	0.9999	430.77 ± 7.84	1.8	6.38 ± 1.80	28.1	<0.1

[a]Number of runs.
[b]Correlation coefficient.
[c]L mol^{-1} s^{-1}.
[d]90% confidence limit.
[e]s^{-1}.
[f]Percentage reaction by S_N1 route at [nucleophile] 10^{-1} mol L^{-1}.

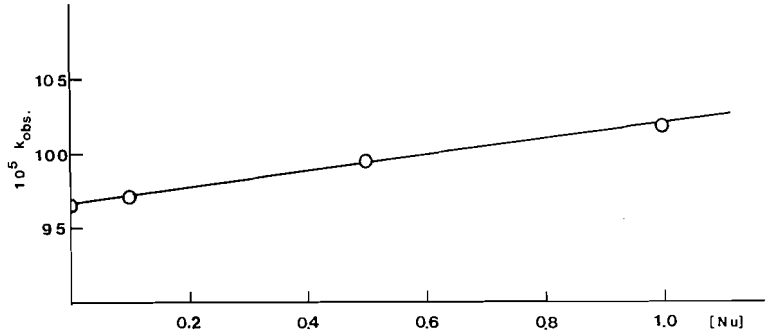


FIG. 4. Plot of observed rate constants for the solvolyses of 1-(*p*-methoxybenzyl)-2,4,6-triphenylpyridinium tetrafluoroborate **1***b* in chlorobenzene at 65.0°C vs. anisole concentration.

pair (mechanism *c*), then the unimolecular modes must in this case be the dissociation of the ion-molecular pair to the free carbocation (mechanism *e*).

Solvolysis of 1-(*p*-methoxybenzyl)-2,4,6-triphenylpyridinium tetrafluoroborate **1***b* was carried out at 65.0°C in chlorobenzene with anisole as nucleophile. As can be seen from Table 6 nucleophilic displacement in this case occurs almost exclusively by an unimolecular S_N1 type mechanism. There is no large rate acceleration when some anisole is added to chlorobenzene solvent. The calculated first-order component (k_1) is the same as that observed for the reaction without the nucleophile.

Conclusions

From Scheme 1, rates for mechanisms (*c*) and (*d*) are proportional to $k'_2[Nu]k_d/(k'_2[Nu] + k_a)$. For mechanism (*c*), $k_a \gg k'_2[Nu]$ and thus the rate is proportional to $k'_2[Nu]k_a/k_d$. For mechanism (*d*), $k'_2[Nu] \gg k_a$ and thus the rate is proportional to k_d. For mechanism (*e*), k''_2 is fast and the rate is proportional to $k_d k'_d/(k_a + k'_d)$. The results presented in this paper are entirely consistent with this scheme and with the operation of two distinct mechanisms at the appropriate borderlines.

Experimental

Ultraviolet spectra of reactants and products were measured on Pye Unicam PU 8800 and Pye Unicam SP6-550 uv–visible spectrophotometers. ^1H nmr spectra were obtained with a Varian Model EM 3604 spectrometer (Me_4Si as internal standard). Infrared spectra were recorded with a Perkin-Elmer Model 283 B spectrophotometer. Melting points (mp) were determined with a Reichart hot stage microscope.

Gas chromatography/mass spectra analysis utilized an AEI MS-30 mass spectrometer (using a Kratos DS-55 data system) interfaced to a Pye 104 gas chromatograph. The column packings employed were 3% SP2100 on 100/120 Supelcoport, 10% Carbowax — 20M/2%KOH (5 or 6 ft × 4 mm) in glass columns, 30 mL/min helium as the carrier gas at flow rates and temperatures specified (Tables 7, 8, 9).

Preparation of compounds

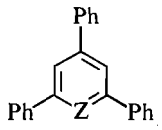
The following were prepared by the literature method quoted: 2,4,6-triphenylpyrylium tetrafluoroborate **1***a*, mp 257°C (lit. (12): 251–257°C); 5,6-dihydro-2,4-diphenylnaphtho[1,2-*b*]pyrylium trifluoromethanesulphonate **2***a*, mp 276°C (lit. (13): 276°C); 5,6-dihydro-2,4-diphenylnaphtho[1,2-*b*]pyrylium tetrafluoroborate **2***b*, mp 268–271°C (lit. (14): 270°C); 5,6,8,9-tetrahydro-7-phenyldibenzo[*c*,*h*]xanthylium trifluoromethanesulphonate **3***a*, mp 304 (lit. (15): 304°C).

General procedure for preparation of pyridinium salts (Scheme 2)

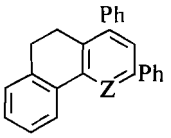
Equimolar quantities of the pyrylium salt, the amine and triethylamine were stirred in dichloromethane (5 mL/g of pyrylium salt) for 2 h. Glacial acetic acid (double molar quantity) was added and the mixture stirred for 24 h. After washing the solution with water, precipitation with ethyl ether gave the products: 1-(*p*-methoxybenzyl)-2,4,6-triphenylpyridinium tetrafluoroborate **1***b*, mp 138–139°C; 1-(2-pentyl)-5,6-dihydro-2,4-diphenylbenzo[*h*]quinolinium trifluoromethanesulphonate **2***c*, mp 141–144°C; 1-(3-pentyl)-5,6-dihydro-2,4-diphenylbenzo[*h*]quinolinium tetrafluoroborate **2***e*, mp 153–154°C (lit. (3*a*): 147–150°C); 1-benzyl-5,6,8,9-tetrahydro-7-phenyldibenzo[*c*,*h*]acridinium trifluoromethanesulphonate **3***b*, mp 170–171°C (lit. (16): 170–171°C).

Kinetic measurements

Kinetics were followed by uv spectrophotometry by monitoring the decrease or the increase of absorbance of the pyridinium salts at fixed wavelengths using the procedure already described (17). Ultraviolet



1



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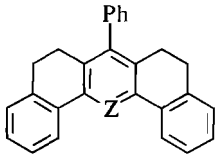

3

1*a*: Z = O^+, (BF_4^-)
1*b*: Z = N^+—$CH_2C_6H_4OCH_3$-*p*, (BF_4^-)
2*a*: Z = O^+, ($CF_3SO_3^-$)
2*b*: Z = O^+, (BF_4^-)
2*c*: Z = N^+—2-pentyl, ($CF_3SO_3^-$)
2*e*: Z = N^+—3-pentyl, (BF_4^-)
3*a*: Z = O^+, ($CF_3SO_3^-$)
3*b*: Z = N^+—$CH_2C_6H_5$, ($CF_3SO_3^-$)

SCHEME 2. Pyrylium and pyridinium salts

cells and sealed glass tubes of 28 cm × 14 mm diameter were used as reaction vessels. Ultraviolet cells were controlled to ±0.5°C in a cell basket inside the uv spectrophotometer by the Pye Unicam Cell Temperature Controller. Glass tubes were controlled to ±1°C in hot blocks (Statim Model 252). For kinetic runs in which the solvent did not contain a basic nucleophile, either small amounts of Et_3N (1×10^{-3} mol L^{-1}) were added, or the kinetic solutions of the pyridinium compounds were diluted to uv concentration (1.4×10^{-5} mol L^{-1}) using an 8% solution of trifluoroacetic acid in chlorobenzene before uv measurement. For solvolyses in the presence of acetic acid and trifluoroacetic acid as nucleophiles, the kinetic solutions of the pyridiniums (1.4×10^{-4} mol L^{-1}) were diluted to uv concentration (2.8×10^{-5} m L^{-1}) using 5% (v/v) solution of triethylamine in chlorobenzene before uv measurement. These procedures converted acid–base equilibrium mixtures into free base or protonated pyridine, respectively (see footnotes to Tables). Pseudo-first-order rate constants were calculated from the slopes of conventional plots of $\ln(\epsilon - \epsilon_2)/(\epsilon - \epsilon_2)$ vs. time (18). Such plots were linear to at least 70% completion, and k_{obs} values were reproducible to ca. 2%.

Solvolysis procedure for gc/ms study

The pyridinium salt in 1.0 mL of solvent was heated with the nucleophile in a sealed glass tube at 65°C for 24 h. The tube was opened immediately before the gc/ms study.

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