Collisionally Activated Dissociation of *N*-Alkylpyridinium Cations to Pyridinium Cation and Olefins in the Gas Phase[1]

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Abstract: Appearance energies (A.E.) are estimated from collisionally activated dissociation (CAD) results for 15 1-substituted pyridinium cations into pyridinium ion and olefins. For nine of these, the alternative dissociation to pyridinium and R^+ was observed. These A.E. were also measured; only in one case do they differ significantly from those for olefin formation. AM1 calculated energies are combined with these A.E. to produce a detailed energy profile for the starting cations, transition states (TS), and products for the butyl family. The TS energy for olefin formation from simple *N*-alkylpyridiniums falls significantly with the number of carbon atoms in R and is much less influenced by the primary, secondary, or tertiary nature of R. This and the energetics indicate an olefinic H-transfer type of transition state with little carbonium ion character. The A.E. values for conversions of *N*-cycloalkylpyridiniums to olefins give evidence of strain energy release.

The background to the work reported in the present pair of papers is described in the introduction to the preceding paper.[1] In that paper, we studied the dissociation of 1-alkylpyridinium cations, Py^+R, to yield pyridine and the corresponding alkyl cation R^+. In a preliminary communication of part of this work,[3] we showed that another important gas-phase dissociation pathway for Py^+R was the formation of pyridinium cation and an olefin. The present paper is concerned with a wide variety of N-substituted pyridinium cations which dissociate entirely or primarily by this second pathway.

Results and Discussion

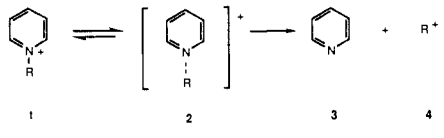
The compounds studied were prepared by standard methods and are listed in Table I. All of these salts were characterized by ^1H and ^{13}C NMR spectroscopy, and details will be published separately.[4]

Fragmentation Pathways. We previously reported[3] the existence of two distinct pathways for the collisionally activated dissociation of compounds **1**: to yield pyridine (**3**) and the corresponding carbocation (**4**) (see Scheme I) or alternatively to produce pyridinium cation and a stable olefin (see Scheme II). The relative importance of these two pathways varies enormously with the structure of the N-substituent. The preceding paper deals with cations (**1**) for which *only* the pathway of Scheme I was observed. We discuss in the present paper the results of 15 compounds for which dissociation to olefin and pyridinium cation (Scheme II) is found: of these, the formation of an alkyl cation and pyridine competes in nine of the compounds.

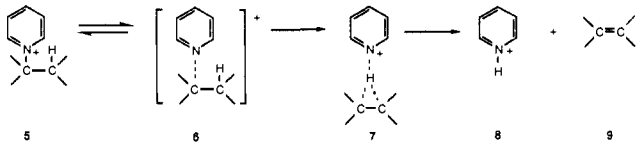
Relative Dissociation Energies. By plotting the percentage of fragmentation $\{100[R^+]/([Py^+R] + [R^+] + [Py^+H])$ or $100\cdot[Py^+H]/([Py^+R] + [R^+] + [Py^+H])\}$ versus the nominal ion center of mass kinetic energy and extrapolating to zero dissociation, the appearance energies of the fragment ions were obtained. A detailed discussion of this procedure is given in the previous paper. Plots are shown in Figures 1-3 for the nine compounds where dissociation occurred by both Scheme I and II. Tables II and III give the experimentally determined appearance energies (A.E.) for fragmentation.

In the nine cases where dissociation by the pathways of Scheme I and Scheme II compete, it was possible to determine independently the individual appearance potentials for both the formation of R^+ plus pyridine and of olefin plus pyridinium ion from plots of the percent fragmentation of Py^+R giving rise to either R^+ or Py^+H versus the nominal ion center of mass kinetic energy.

Scheme I. Fragmentation to Pyridine and Carbocation



Scheme II. Fragmentation to Pyridinium Cation and Alkene



To determine whether or not two daughter fragment ions had a common appearance energy, χ^2 values were calculated for (i) the weighted least-squares fits and (ii) lines that were forced to have given *x*-intercepts. Listed in Table IV are the calculated χ^2 values when both fragments are forced to have the same *x*-intercept (appearance energy). By forcing the extrapolated lines through these constant *x*-intercepts and varying the slopes, the minimum χ^2 values were calculated for the given *x*-intercept. Comparison of the fits based on the magnitude of χ^2 listed in Table IV suggest that eight of the nine compounds share a common appearance energy. Only cyclopropylmethylpyridinium (**1m**) appears to have different appearance energy. Hence we can conclude that **2** and **6** are identical in the eight cases. However, for the *N*-cyclopropylmethyl (**1m**) compound, the A.E. appears to be significantly *different* for the two processes.

Fragmentation to Pyridinium and Alkyl Cations. Fragmentation of this type is a competing pathway for the nine compounds listed in Table II.

Heats of formation were calculated as before[1] for the starting pyridinium ions Py^+R and for the alkyl cations R^+. By using these ΔH_f values, the minimum (i.e., assuming no activation energy barrier) theoretical heats of dissociation $\Delta\Delta H_f$ for the process of Scheme I were calculated with eq 1.

$$\Delta\Delta H_f = [\Delta H_f(\mathrm{Py}) + \Delta H_f(\mathrm{R}^+)] - \Delta H_f(\mathrm{Py}^+\mathrm{R}) \qquad (1)$$

The appearance potentials are plotted against $\Delta\Delta H_f$ values in Figure 4. As can be seen from this figure, the cations of Table II can be divided into three groups. The only compound in the first group, cyclopentyl (**1k**), showed an A.E. almost identical with the calculated $\Delta\Delta H_f$ activation barrier for the formation of the

(1) Part 27 in the series *Kinetics and Mechanisms of Nucleophilic Displacements with Heterocycles as Leaving Groups*. For part 26, see: Katritzky, A. R.; Watson, C. H.; Dega-Szafran, Z.; Eyler, J. R. *J. Am. Chem. Soc.*, preceding paper in this issue.

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(3) Watson, C. H.; Baykut, G.; Mowafy, Z.; Katritzky, A. R.; Eyler, J. R. *Anal. Instrum.* **1988**, *17*, 155.

(4) Katritzky, A. R.; Dega-Szafran, Z. *Magn. Res. Chem.* **1989**, 27, 1091.

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Table I. Preparation of the 1-Substituted Pyridinium Salts

compd no.	1-substituent R	anion X	preparation time, h	preparation temp, °C	preparation solvent	crystallization solvent[a]	crystallization form	yield, %	mp (°C) found	mp (°C) lit.	ref
1a	CH_3CH_2	Br	10	22		A-Et	m.cryst	91	116–118	120–121	5
1b	$C_2H_5O_2CCH(CH_3)$	ClO_4	20	22		A	m.cryst	62	73–74[b]		c
1c	$(CH_3)_2CH$	ClO_4	6	0	CH_3NO_2	A	m.cryst	43	112	112	6
1d	cyclohexyl-CH_2	ClO_4	12	22		A	prisms	24	122–123[b]	*e*	
1e	$CH_3CH_2CH_2$	Br	24	80		A-Et	m.cryst	64	75–76	81	7
1f	$CH_3CH_2CH_2CH_2$	I	24	22		A-Et	prisms	98	67–68[b,d]	182 dec	7
1g	$C_2H_5O_2CCH_2CH_2$	Br	12	100		A	m.cryst	85	69–70	70–72	8
1h	$(CH_3)_2CHCH_2$	Br	24	80		A-Et	m.cryst	65	63–65[b,d]	*f*	9
1i	$CH_3CH_2CH(CH_3)$	Br	96	22		A-Et	m.cryst	92	69–70[b,d]	*f*	9
1j	$(CH_3)_3C$	ClO_4	6	0	CH_3NO_2	A	plates	28	215–217	215–217	6
1k	$(C_2H_5)_2CH$	Br	24	34	$(C_2H_5)_2O$	A-Et	m.cryst	37	285–290[b]	*e*	
1l	cyclopentyl	ClO_4	48	34	$(C_2H_5)_2O$	A	m.cryst	34	85–86[b,d]	*e*	
1m	cyclopropyl-CH_2	ClO_4	20	80		A-Et	prisms	97	90–92[b]	*e*	
1n	cyclobutyl-CH_2	ClO_4	24	70		A-Et	plates	76	67–69[b]	*e*	
1o	$C_6H_5CH(CH_3)$	ClO_4	3	22		A-Et	needles	82	92–93	92–94	10

[a] A, ethanol; Et, diethyl ether; Ac, acetone; m.cryst, microcrystals. [b] Correct analysis in Experimental Section. [c] Known as picrate, ref 8. [d] Contain water of crystallization. [e] New compound. [f] Reference quoted gives no mp.

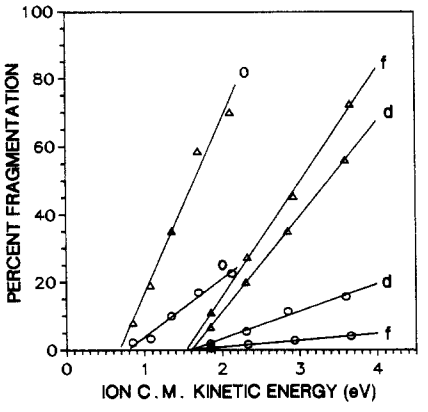


Figure 1. Percent fragmentation of Py^+R to Py^+H (△) and olefin and R^+ (○) and Py versus nominal ion center of mass energy for some 1-substituted pyridinium cations (**1**): cyclohexylmethyl (**d**); *n*-butyl (**f**); α-phenylethyl (**o**).

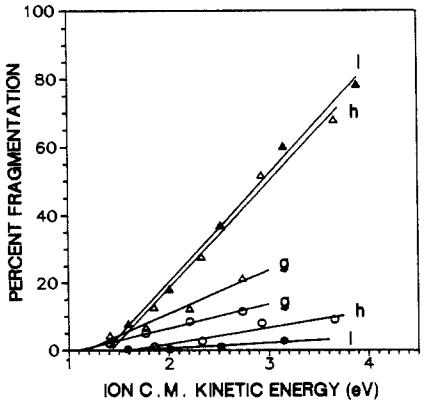


Figure 2. Percent fragmentation of Py^+R to Py^+H (△ or ▲) and olefin and R^+ (○ or ●) and Py versus nominal ion center of mass energy for some 1-substituted pyridinium cations (**1**): β-(ethoxycarbonyl)ethyl (**g**); isobutyl (**h**); cyclopentyl (**l**).

cyclopentyl cation, a cation which cannot easily rearrange into a more stable species.

The second group comprises five compounds for which the A.E. is significantly lower than the $\Delta\Delta H_f$ calculated for dissociation without rearrangement. In the isobutyl (**1h**), *n*-butyl (**1f**), cyclohexylmethyl (**1d**), cyclobutylmethyl (**1n**), and 2-(ethoxycarbonyl)ethyl (**1g**) compounds, the A.E. is lower by ca. 12, 15, 7, 26, and 19 kcal/mol, respectively. This indicates that the corresponding cations all undergo considerable reorganization at the ion–molecule complex stage. Indeed, in all these cases rearranged species are expected to be considerably more stable. We

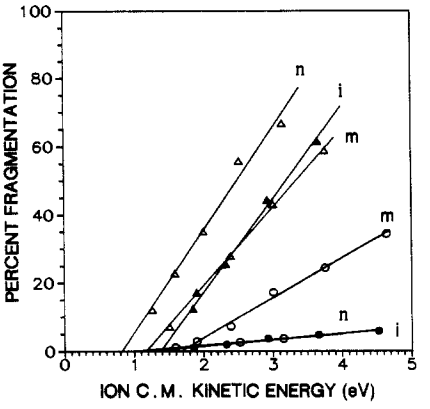


Figure 3. Percent fragmentation of Py^+R to Py^+H (△ or ▲) and olefin and R^+ (○ or ●) and Py versus nominal ion center of mass energy for some 1-substituted pyridinium cations (**1**): *sec*-butyl (**i**); cyclopropylmethyl (**m**); cyclobutylmethyl (**n**).

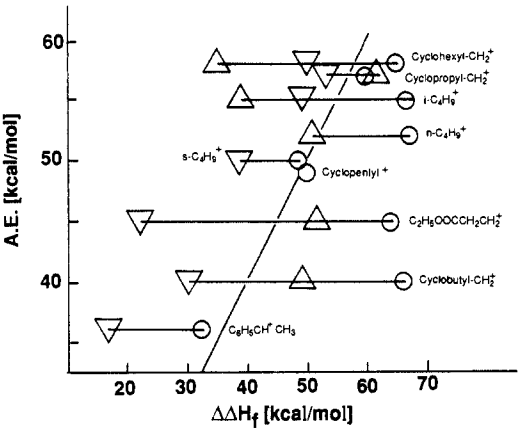
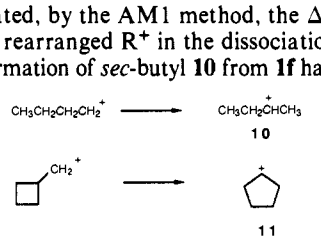


Figure 4. Plot of experimentally determined appearance energies against calculated heats of formation ($\Delta\Delta H_f$) of $Py^+R \rightarrow Py + R^+$: (○) simple cation; (△), rearranged cation, H migration; (▽), rearranged cation, C migration; data from Table II.

therefore calculated, by the AM1 method, the $\Delta\Delta H_f$ values for the formation of rearranged R^+ in the dissociation reaction and found that the formation of *sec*-butyl **10** from **1f** has a $\Delta\Delta H_f$ value



which is ca. 1 kcal/mol *below* the A.E. (see Table II); this process

Table II. Energetics (kcal/mol) of Fragmentation of 1-Substituted Pyridinium Cations (**1**) to Pyridine and Alkyl Cation

compd no.	1-substituent R	appearance energy of R^+[a]	R^+ internal energy (350 K)[b]	corrected appearance energy (350 K)[c]	ΔH_f (AM1) Py^+R	ΔH_f (AM1) R^+ simple	R^+ rearr[d] H[g]	R^+ rearr[d] C[g]	$\Delta\Delta H_f$[e] (AM1) simple	$\Delta\Delta H_f$[e] (AM1) rearr[d] H[g]	$\Delta\Delta H_f$[e] (AM1) rearr[d] C[g]
1d	cyclohexyl-CH_2	49	6	58	153	186	156	171	65	35	50
1m	cyclopropyl-CH_2	50	4	57	206	234	235	226	60	61	53
1h	$(CH_3)_2CHCH_2$	48	4	55	167	202	174	184	67	39	49
1f	$CH_3CH_2CH_2CH_2$	44	5	52	165	200	184		67	51	
1i	$CH_3CH_2CH(CH_3)$	42	5	50	167	184		174	49		39
1l	cyclopentyl	42	4	49	168	186			50		
1g	$C_2H_5O_2CCH_2CH_2$	35	7	45	99	131	119[f]	89[f]	64	52[f]	22[f]
1n	cyclobutyl-CH_2	32	5	40	188	222	204	186	66	48	30
1o	$C_6H_5CH(CH_3)$	27	6	36	207	207		191	32		17

[a] Corrected for energy spread in ions and neutrals, see previous paper. [b] Calculated or estimated as discussed in previous paper. [c] For the process Py^+–R (350 K) → Py (350 K) + R^+ (350 K). Internal energy of Py (350 K) = 0.12 eV (3 kcal/mol) has been added to the sum of the previous two columns. [d] Rearr, rearranged. [e] See eq 1, ΔH_f(Py) = 32.1 kcal/mol.[11] [f] H column refers to **12**, C column to **13**. [g] H or C migration.

Table III. Energetics (kcal/mol) of Fragmentation of 1-Substituted Pyridinium Cations (**1**) to Protonated Pyridine and Olefin

compd no.	1-substituent R	appearance energy of Py^+H[a]	olefin internal energy (350 K)[b]	corrected appearance energy (350 K)[c]	ΔH_f (AM1) Py^+R	ΔH_f (AM1) R^+	ΔH_f (AM1) olefin	ΔH_f (exptl)[d] R^+	ΔH_f (exptl)[d] olefin	$\Delta\Delta H_f$[e] R^+[f]	$\Delta\Delta H_f$[e] olefin[g]
1a	CH_3CH_2	62	2	67	179	217	16	216	14	70	22
1b	$C_2H_5O_2CCH(CH_3)$[h]	51	6	60	95	134	−75			71	14
1c	$(CH_3)_2CH$	50	2	55	174	192	7	193	5	51	17
1d	cyclohexyl-CH_2	45	5	53	153	186	−14[i]	171	−10	65	17
1e	$CH_3CH_2CH_2$	47	2	52	172	208	7	212	5	68	20
1f	$CH_3CH_2CH_2CH_2$	45	4	52	165	200	0	203	0	67	20
1g	$C_2H_5O_2CCH_2CH_2$[h]	42	6	51	99	131	−75			64	9
1h	$(CH_3)_2CHCH_2$	43	3	49	167	202	−1	199	−4	67	16
1i	$CH_3CH_2CH(CH_3)$	38	4	45	167	184	−2	183	−2	49	15
1j	$(CH_3)_3C$	38	3	44	172	174	−1	166	−1	34	12
1k	$(CH_3CH_2)_2CH$	35	5	43	161	177	−9	175	−6	48	14
1l	cyclopentyl	36	3	42	168	186	3	191	9	50	19
1m	cyclopropyl-CH_2	33	3	39	206	234	48[j]		48	60	26
1n	cyclobutyl-CH_2	27	4	34	188	222	25		30	66	21
1o	$C_6H_5CH(CH_3)$	23	5	31	207	207	39	199	35	32	16

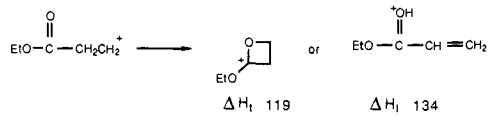
[a] Corrected for energy spread in ions and neutrals, as discussed in previous paper. [b] Calculated or estimated as described in the previous paper. [c] For the process Py^+R (350 K) → Py^+H (350 K) + olefin (350 K). Internal energy of Py^+H (350 K) = 0.12 eV (3 kcal/mol) has been added to the sum of the previous two columns. [d] From ref 12 and 13. [e] From ΔH_f values calculated by AM1 method. [f] See eq 1; ΔH_f(Py) = 32.1 kcal/mol.[11] [g] See eq 2, $\Delta H_f(Py^+H)$ = 184.2 kcal/mol.[14] [h] Formed other ions, see text. [i] Cycloheptene, ΔH_f = 11 kcal/mol. [j] Cyclobutene, ΔH_f = 46 kcal/mol.

Table IV. Comparison of Slopes and Intercepts of Percent Fragmentation for Formation of R^+ and of Py^+H

compd no.	1-substituent	fragment	best fit[a] x-int.[c]	best fit[a] slope	best fit[a] χ^2[d]	forced fit[b] x-int.[c]	forced fit[b] slope	forced fit[b] χ^2
1d	cyclohexyl-CH_2	Py^+H	1.60	28.20	0.01	1.64	29.03	0.17
		R^+	1.65	8.82	0.74	1.60	8.41	0.93
1m	cyclopropyl-CH_2	Py^+H	1.20	23.51	0.14	1.70	29.39	83.14
						1.45	29.08	12.87
		R^+	1.70	12.28	1.48	1.20	9.21	20.44
						1.45	9.55	6.10
1h	$(CH_3)_2CHCH_2$	Py^+H	1.51	35.45	0.19	1.65	41.19	1.52
						1.58	38.25	0.48
		R^+	1.65	4.51	1.22	1.51	3.60	2.16
						1.58	4.03	1.50
1f	$CH_3CH_2CH_2CH_2$	Py^+H	1.50	31.81	0.03	1.49	31.75	0.04
		R^+	1.49	1.93	0.05	1.50	1.94	0.06
1i	$CH_3CH_2CH(CH_3)$	Py^+H	1.41	27.94	0.50	1.38	27.49	0.54
		R^+	1.38	2.05	0.63	1.41	2.10	0.66
1l	cyclopentyl	Py^+H	1.43	34.43	0.71	1.39	33.32	0.88
		R^+	1.39	1.05	0.66	1.43	1.10	0.67
1g	$C_2H_5O_2CCH_2CH_2$	Py^+H	1.39	17.68	13.73	1.12	14.49	22.28
						1.25	15.97	15.70
		R^+	1.12	7.27	0.75	1.39	9.03	12.84
						1.25	8.11	3.11
1n	cyclobutyl-CH_2	Py^+H	0.95	34.17	0.27	0.99	35.87	0.36
		R^+	0.99	1.66	0.07	0.95	1.61	0.27
1o	$C_6H_5CH(CH_3)$	Py^+H	0.73	17.86	0.15	0.81	16.63	1.67
		R^+	0.81	16.44	1.38	0.73	14.07	2.09

[a] Weighted least-squares fit; ref 15. [b] Line forced to have x-intercept shown. [c] Electon volts. [d] $\chi^2 = \sum w_i(Y_{calc} - Y_{obs})^2$.

is well-established in solution chemistry.[16,17] Similarly, rearrangement of isobutyl **1h** to *tert*-butyl affords a much more stable cation. Again, the cyclohexylmethyl and cyclobutylmethyl cations are known[18-20] to rearrange into methylcyclohexyl and/or cycloheptyl and into methylcyclobutyl and/or cyclopentyl cations (**11**), respectively, and the $\Delta\Delta H_f$ values for formation of such rearranged species now fit well with the observed A.E. values (see Figure 4 and Table II). Rearrangement of 2-(ethoxycarbonyl)-ethyl (**1g**) to (**12**) (as in solution[21]) affords insufficient energy, whereas rearrangement to **13** gives a $\Delta\Delta H_f$ which is ca. 20 kcal/mol *below* the A.E.



12 13

For the remaining three cases, the situation is less clear cut with A.E. values close to the $\Delta\Delta H_f$ for the formation of unrearranged R^+. It thus appears that in the ion–molecule complex of 1-phenylethyl (**1o**) (A.E. = $\Delta\Delta H_f$ +4 kcal/mol) little or no rearrangement occurs to methyltropylium, of *sec*-butyl (**1i**) (A.E. = $\Delta\Delta H_f$ +1 kcal/mol) to *tert*-butyl, and of cyclopropylmethyl (**1m**) (A.E. = $\Delta\Delta H_f$ −3 kcal/mol) to cyclobutyl. By analogy with solution results,[22] rearrangements are less facile in these systems, and the carbonium ions initially formed are more stable.

Strikingly, these three groups can be differentiated in another way. The cation in the first group cannot rearrange into a more stable cation by simple H or C migration. The second group of cations can all be at least partly stabilized by a H^- migration. The third group can be stabilized only by a C migration, known[18,20] to be more difficult than a H^- migration. Furthermore, the single case (**1m**) for which we have evidence that the intermediates **2** and **6** are not identical belongs to this third group of pyridinium cations.

All in all, the results for these nine pyridinium compounds reacting by pathway 1 (Scheme I) confirm and amplify the conclusions reached in the preceding paper.

Fragmentation to Pyridinium Ion and Olefin. The theoretical heats of dissociation $\Delta\Delta H_f$ for the processes of Scheme II were calculated by AM1 with eq 2.

$$\Delta\Delta H_f = [\Delta H_f(Py^+H) + \Delta H_f(\text{olefin})] - \Delta H_f(Py^+R) \quad (2)$$

In view of the work of Bowen,[23] we also calculated the energies for the decomposition **14** → **15** + olefin. The ΔH_f for the non-

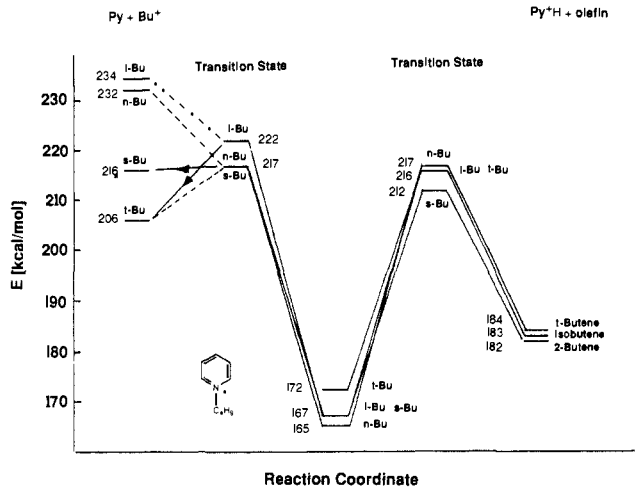
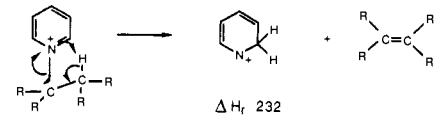


Figure 5. Energy profile for the dissociation of *N*-butylpyridinium cations Py^+R into Py and R^+ and into Py^+H and olefin.

aromatic cation (**15**) is calculated to be 232 kcal/mol, i.e., 48 kcal/mol higher in energy than that of the isomeric aromatic cation (**8**). In Table III, adding 48 kcal/mol to the values shown in the last column of $\Delta\Delta H_f$ olefin values gives new $\Delta\Delta H_f$ values for the formation of olefin and which in all cases are higher and in many cases very considerably higher than the corrected A.E. values. We believe this excludes **15** as a usual intermediate.



14 15

The values for ΔH_f for olefins in Table III refer to the olefin formed without skeletal rearrangement, e.g., in the butyl series, to isobutene from both isobutyl- (**1h**) and *tert*-butylpyridinium (**1j**) and to 1-butene from *n*-butyl (**1f**). From *sec*-butylpyridinium (**1i**), three isomeric olefins can be formed without skeletal rearrangement, but which is formed is of little significance as their ΔH_f values are so close: 1-butene (ΔH_f = 0 kcal/mol), *cis*-2-butene (ΔH_f = −2 kcal/mol), and *trans*-2-butene (ΔH_f = −2 kcal/mol). For the pathway of Scheme II, the estimated A.E. are all greater than the corresponding calculated $\Delta\Delta H_f$ value for olefin formation (cf. Table III). However, the magnitude of the activation barrier, calculated by adding the experimental A.E. to the ΔH_f of Py^+R calculated by using AM1, varies considerably. The reverse activation barrier (reverse $\Delta H^{\ddagger}$), calculated by subtracting the AM1 calculated energy from the transition state energy, is always appreciable.

Simple Alkyl Groups. For simple alkyl groups both the A.E. for olefin formation *and* the calculated height of the transition state above the products (unsubstituted pyridinium cation and olefin) (reverse $\Delta H^{\ddagger\prime}$) decrease with the number of carbon atoms contained in the *N*-alkyl group:

$$\text{Et} > i\text{-Pr, Pr} > \left\{\begin{matrix} n\text{-Bu, } i\text{-Bu} \\ sec\text{-Bu, } t\text{-Bu} \end{matrix}\right\} > \left\{\begin{matrix} \text{3-pentyl} \\ \text{cyclo-pentyl} \end{matrix}\right\}$$

A.E. =	67	55–52	52–44	43–42 kcal/mol
reverse $\Delta H^{\ddagger\prime}$ =	46	38–32	33–32	29–23 kcal/mol

The dependence of both the A.E. and the TS energy for olefin formation on the number of carbon atoms involved is more important than on the nature of the alkyl group (primary, secondary, or tertiary). This is quite in contrast to the ΔH_f values for the formation of R^+ ions, which depend very significantly on the primary, secondary, or tertiary nature of R: thus $n\text{-Bu}^+$ and $t\text{-Bu}^+$ differ by 26 kcal/mol (see Table IV of preceding paper). This difference implies that R^+ character does not dominate in the transition state (**6**) leading to the olefin formation. By implication, the difference also implies that R^+ character does not dominate

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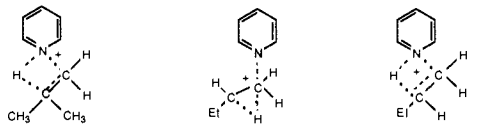
in the transition state (**2**) leading to neutral pyridine and R^+; further evidence for this conclusion is discussed below.

A rather complete picture is available for the family of butylpyridinium cations (Figure 5). The transition-state energies for the decomposition of the four isomers into Py^+H and olefin, obtained by adding the A.E. to the ΔH_f for the corresponding cations, are spaced within 5 kcal/mol. For *n*-butyl (**1f**) and for isobutyl (**1h**), this TS energy is well below the sum of the energies of the corresponding free R^+ and Py (see Figure 5). This suggests that for *n*-butyl (**1f**) and isobutyl (**1h**) the reaction path for olefin formation involves a rearrangement of type **16**. For *sec*-butyl (**1i**) and *tert*-butyl (**1j**), by contrast, the reaction path could involve considerable free cation character, as the TS energies for olefin formation for *sec*-butyl and *tert*-butyl are close to or above the energies for the corresponding simple unrearranged R^+ cations.

For *n*-butyl (**1f**), isobutyl (**1h**), and *sec*-butylpyridiniums (**1i**) the TS energies for the alternate decompositions to alkyl cation R^+ and pyridine and to the pyridinium ion and an olefin are not significantly different (see Table IV and discussion above), and the TS may be identical for the two pathways. For *n*-butyl (**1e**) and isobutyl (**1h**), the TS energies for the formation of R^+ (and also the TS energies for the formation of the olefin) are both significantly lower than the energies for formation of the free *n*-butyl and isobutyl cations (Figure 5); this indicates rearrangements into *sec*-butyl and *tert*-butyl cations, respectively, and TS of the types **17** and **18**. for *sec*-butyl (**1i**) the R^+ cation could be formed with or without rearrangement. We do not see any formation of $t\text{-}Bu^+$ and cannot therefore measure an A.E. for it. Figure 5 suggests further that the TS for the decomposition of both *n*-butyl- (**1f**) and *sec*-butylpyridinium (**1i**) into R^+ and pyridine may be identical, i.e., of type **2** with R essentially *sec*-butyl.



16 **17** **18**

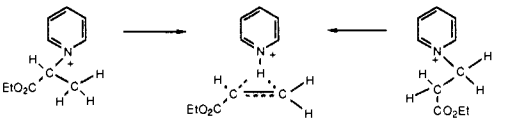
For the ethyl- (**1a**), *n*-propyl- (**1e**), and isopropyl- (**1c**) pyridiniums, the TS energies for olefin formation at 246, 229, and 224 kcal/mol, respectively, are all either the same as isopropyl or somewhat lower than ethyl and *n*-propyl, the corresponding energies for Py and R^+ at 249, 240 and 224 kcal/mol, respectively. Although it is difficult to rule out olefin formation via free R^+ in these cases from an energetic viewpoint, as we detected no formation of R^+ for any of them, we believe rather that TS structures of the type **16** are implicated in these olefin formations.

For the 3-pentyl (**1k**) and cyclopentyl (**1l**) compounds the TS energies for olefin formation at 204 and 210 kcal/mol are each somewhat below the sum of the energies for Py + R^+ at 209 and 218 kcal/mol, respectively. This again indicates the reaction paths to be of type **16**.

Cycloalkylmethyl. For cyclohexylmethyl (**1d**) we find a high activation barrier (53 kcal/mol) for olefin formation compared to that expected (see discussion above) for *n*-hexyl on the basis of the results for the propyl, butyl, and pentyl homologs. The TS energy at 206 kcal/mol is still below the R^+ + Py energy (218 kcal/mol).

For cyclobutylmethyl (**1n**) and cyclopropylmethyl (**1m**) the barriers to olefin formation (39 and 34 kcal/mol) are smaller, suggesting that strain is released in the TS and that rearranged olefins are formed. The TS energy for olefin formation for the cyclobutylmethyl compound at 222 kcal/mol is below the calculated energy for formation of free cyclobutylmethyl cation (228 kcal/mol), suggesting that cyclopentene is the olefin produced. For the cyclopropylmethyl compound (**1m**), the TS energy for olefin formation (245 kcal/mol) is also below that for formation of free R^+ (263 kcal/mol), although above the energies for formation of methylenecyclopropane (213 kcal/mol) and close to the energy needed for the formation of cyclobutene (230 kcal/mol).

Scheme III



1b **19** **1g**

(Ethoxycarbonyl)alkyl Compounds. The activation barrier for the formation of ethyl acrylate from α-pyridiniopropionate (**1b**) is 9 kcal/mol above that from the β-pyridiniopropionate (**1g**). In solution, the β-derivative (**1g**) would be expected to undergo facile elimination via a reverse Michael mechanism (elimination via conjugate base), whereas **1b** would be rather stable toward elimination.

The TS energies for olefin formation from **1b** and **1g** at 155 and 150 kcal/mol, respectively, are both lower than the energies calculated for formation of the corresponding simple R^+ + Py pairs at 166 and 163 kcal/mol. Only from **1g** do we find R^+ formation. These facts suggest that the TS for olefin formation from both **1b** and **1g** has a structure of type **19** (cf. Scheme III).

The 1-(1-(ethoxycarbonyl)ethyl)pyridinium cation (**1b**) produced two fragment ions upon collisionally activated dissociation (*m/z* 152 and *m/z* 80). The major fragmentation pathway produced an ion with *m/z* 152 corresponding to loss of C_2H_4. The second fragment ion corresponded to dissociation via Scheme II.

Four fragment ions were produced by CAD of the 1-(2-(ethoxycarbonyl)ethyl)pyridinium cation (**1g**). The fragment ion of greatest abundance was *m/z* 152 resulting from loss of C_2H_4. Ions with *m/z* 80, 73, and 101 of lower abundance were also observed.

General Conclusions of This Paper and the Preceding Paper. Collisionally activated dissociation is demonstrated to be a powerful method for investigating S_N1 type reactions of the classical aliphatic R–X type in the gas phase. The alternative dissociations into R^+ (and pyridine) or into olefin (and pyridinium cation) most often, but not always, appear to involve the same transition state. The energy of the TS for R^+ formation is dominated by the possibility of rearrangement into a more stable isomer R'^+; where no such reorganization is possible, the TS shows an energy close to that of the free R^+. When $R^+ \rightarrow R'^+$ is energetically favored, A.E.'s far below the energy of unrearranged R^+ plus pyridine are found. These facts tend to equalize the TS energies for the dissociation of isomeric *N*-alkylpyridiniums, as illustrated by the butyl series.

The TS for olefin formation for simple alkyl groups is dominated by the size of R, falling dramatically with increase in the number of carbon atoms, and again is much less influenced by the primary, secondary, or tertiary nature of R. This and the energetics indicate that the reaction path involves considerable olefinic character. Evidence for steric strain release is shown in olefin formation from the cycloalkylmethyl compounds.

Experimental Section

Mass spectrometric studies were carried out with a Nicolet FT/MS-1000 Fourier transform ion cyclotron mass spectrometer equipped with a 3 T superconducting magnet. Gas-phase pyridinium ions were produced by direct laser desorption. For details of the experimental setup and analysis of data see the preceding paper.[1]

Theoretical calculations were performed by the AM1 method[24] with the MOPAC program (Version 3.0)[25] on a MicroVAX II. For details see ref 1.

Salts were obtained from pyridine and the corresponding alkyl halide. The details are given in Table I. However all attempts to obtain *N*-cyclohexylpyridinium salts from cyclohexyl halides and pyridine led only to elimination and indeed no *N*-cyclohexylpyridinium salt has been reported.

1-(1-(Ethoxycarbonyl)ethyl)pyridinium Perchlorate (1b). Anal. Calcd for $C_{10}H_{14}ClNO_6$, C, 42.95; H, 5.05; N, 5.01. Found: C, 42.64; H, 4.93; N, 5.00. **1-(Cyclohexylmethyl)pyridinium Perchlorate (1d).** Anal. Calcd for $C_{10}H_{14}ClNO_4 \cdot 0.5H_2O$: C, 46.79; H, 5.89; N, 5.46.

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Found: C, 47.11; H, 5.69; N, 5.31. **1-(*n*-Butyl)pyridinium Iodide (1f)**, Anal. Calcd for $C_9H_{14}IN \cdot 0.5H_2O$: C, 39.72; H, 5.56; N, 5.17. Found: C, 40.04; H, 5.58; N, 5.17. **1-(2-Methylpropyl)pyridinium Bromide (1h)**, Anal. Calcd for $C_9H_{14}BrN \cdot H_2O$: C, 46.17; H, 6.89; N, 5.98. Found: C, 45.90; H, 7.01; N, 5.70. **1-(1-Methylpropyl)pyridinium Bromide (1i)**. Anal. Calcd for $C_9H_{14}BrN \cdot H_2O$: C, 46.17; H, 6.89; N, 5.98. Found: C, 46.25; H, 6.52; N, 6.10. **1-(Cyclopentyl)pyridinium Perchlorate (1l)**, Anal. Calcd for $C_{10}H_{14}ClNO_4 \cdot H_2O$: C, 42.64; H, 5.73; N, 4.97. Found: C, 42.66; H, 5.63; N, 4.77. **1-(Cyclopropylmethyl)pyridinium Perchlorate (1m)**. Anal. Calcd for $C_9H_{12}ClNO_4$: C, 46.27; H, 5.18; N, 5.99. Found: C, 46.26; H, 5.16, N, 5.97. **1-(Cyclobutylmethyl)pyridinium Perchlorate (1n)**, Anal. Calcd for $C_{12}H_{18}ClNO_4$: C, 52.27; H, 6.58; N, 5.08. Found: C, 51.87; H, 6.50; N, 5.14.

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Target Gas Excitation in Collision-Induced Dissociation: A Reinvestigation of Energy Loss in Collisional Activation of Molecular Ions of Chlorophyll-*a*†

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Abstract: Losses of translational energy accompanying collisional activation (CA) of large organic ions at keV energies have been found to be unexpectedly large, as exemplified by work of Bricker and Russell (*J. Am. Chem. Soc.* **1986**, *108*, 6174) on molecular ions of chlorophyll-*a*. These energy shifts are of practical importance for tandem mass spectrometry applied to biochemistry and are also of theoretical interest with respect to the very large kinetic shifts thus implied for the dissociation. The original work attributed the chlorophyll-*a* shifts to ionization of collision target molecules as a mandatory accompaniment to CA, with negligible contributions from kinetic shift to the observed inelasticity. The present work has exploited improved experimental techniques to demonstrate that those trends observed by Bricker and Russell, which led to their target ionization hypothesis, were experimental artifacts and that target mass rather than ionization energy is the dominant parameter in determining the energy shift. Angular dependences of these energy shifts have been determined and shown to be consistent with predictions based on theoretical calculations of scattering effects based upon the limiting "elastic model" for inelastic collisions. These calculations required only one arbitrarily adjustable parameter (the magnitude of the average energy deposition leading to dissociation) and can account semiquantitatively for energy shifts as well as qualitatively for variations in peak shapes. The limitations of the present approach have also been assessed.

Tandem mass spectrometry has become a widely accepted approach to structural analysis,[1] more recently in the context of larger molecules of biochemical interest. The dissociation of precursor ions, which have been subjected to collisional activation (CA) via collisions at keV energies with a target gas, is often characterized[2] by a substantial loss of translational energy of the precursor (E_p). Of course the conversion of translational to internal energy provides the basis for the CA method, but the surprisingly large magnitudes observed for some of these energy-loss shifts, particularly for larger ions, have raised interest in the phenomenon for both practical and theoretical reasons. Thus the widely used technique of mass-analyzed ion kinetic energy spectrometry (MIKES[3]) is subject to the direct effect of such shifts, which greatly reduce confidence in the fragment masses assigned to the observed peaks. If a double-focussing combination of electric plus magnetic sectors is used as the fragment ion analyzer, the energy focussing properties ensure that mass assignments are not affected by energy-loss shifts. However a significant loss in sensitivity can result since the linked-scan relationship for such analyzers is usually calculated on the assumption that such shifts are negligible; by electrically floating the collision region above ground, these practical problems can be alleviated to some extent.[4] The more theoretical interest in these apparently anomalously large energy losses concerns the large kinetic shifts thus implied for the subsequent dissociation of the collisionally activated ions, on the appropriate time scale (few μs).

A widely quoted example of this phenomenon was reported by Bricker and Russell,[5] who studied the collision-induced dissociation (CID) of ions produced by fast atom bombardment (FAB) ionization of chlorophyll-*a*. The major fragmentation reaction, m/z 893.5 → m/z 614.2, was studied[5] with different inert gases as collision partners by using the MIKES technique. By assuming that the MIKES peak corresponded to fragment ions of m/z 614 (with no unresolved ions of m/z within a few Da of this value), an assumption later verified,[6] it was possible[5] to predict the position of the peak on the translational energy scale. The experimentally observed energy shifts ΔE_F, thus measured for the fragment ions, were converted to the corresponding shifts for the precursors via the simple relation

$$\Delta E_p = \Delta E_F \cdot (m_p/m_F) \quad (1)$$

where m_p and m_F are the masses of precursor and fragment ions, respectively. The values of ΔE_p thus obtained[5] were remarkably

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