

Acid-catalyzed Hydrolyses of Bridged Bi- and Tricyclic Compounds. VIII.* Kinetics of 2-Methyl-*exo*-2-norbornenyl Acetate and Its Intermediate Products in Dioxane—Water Mixtures

MARTTI LAJUNEN and HEIKKI LYYTIKÄINEN

Department of Chemistry and Biochemistry, University of Turku,
SF-20500 Turku 50, Finland

Solvent effects on the hydrolysis of 2-methyl-*exo*-2-norbornenyl acetate (*exo*-II-OAc) and its intermediate products, 2-methyl-*exo*-2-norbornenol (*exo*-II-OH) and 1-methyl-3-nortricyclanols (*trans*- and *cis*-III-OH), have been measured with 1-methyl-cyclopentyl and 1-methylcyclohexyl acetates as reference substrates in dioxane-water mixtures under catalysis of perchloric acid. The ratio of the formation rates of the unrearranged bicyclic and rearranged tricyclic intermediate products does not significantly change with changing dioxane content. Formation of the tricyclic products is stereoselective: *trans*-III-OH:*cis*-III-OH = 14:1 (0 and 55.5 wt. % dioxane). The results agree better with a bridged homoallylic carbocation than with equilibrating classical bi- and tricyclic carbocations.

Former papers^{1,2} dealt with the acid-catalyzed hydrolyses of several secondary and methyl-substituted tertiary norbornyl and norbornenyl acetates, which were investigated in dioxane-water mixtures. By employing the modified Foote-Schleyer relationship for estimation of the "normal" hydrolysis rates of the tertiary acetates, anchimeric increase of rate was evaluated in the case of 2-methyl-*exo*-2-norbornyl (*exo*-I-OAc) and 2-methyl-*exo*-2-norbornenyl (*exo*-II-OAc) acetates. The *exo/endo* rate ratios were measured to be 630 and 130, respectively, at 25 °C (only the A_{AL} mechanism is included).

Criticism has been presented against employing both the "normal" rates, estimated by the

Foote-Schleyer method, and the *exo/endo* rate ratios as measures of the anchimeric assistance.³ However, an increase in the *exo/endo* rate ratios has been observed in the solvolysis of 5-methyl-2-aryl-norbornenyl esters with increasing π participation as measured from the amount of the rearranged tricyclic products.⁴ Hence, the *exo/endo* rate ratio of 130 measured for 2-methyl-2-norbornenyl acetates seems to be rather small. Therefore, more studies were carried out in order to determine the character of the transition state and of carbocation intermediate(s) in the hydrolysis of 2-methyl-*exo*-2-norbornenyl acetate (*exo*-II-OAc). The solvent effects on its disappearance rates and on the formation and disappearance rates of its intermediate products, 2-methyl-*exo*-2-norbornenol (*exo*-II-OH) and 1-methyl-3-nortricyclanols (III-OH), were investigated in dioxane-water mixtures and the results were compared with those of 1-methylcyclopentyl (Pen-OAc) and 1-methylcyclohexyl (Hex-OAc) acetates.

EXPERIMENTAL

The preparation of 2-methyl-*exo*-2-norbornenol (purity 97 % by GLC)⁵ and 1-methyl-3-nortricyclanols (purity of *trans* isomer was 98 % and that of *cis* isomer 76 % by GLC; the impurity consisted of the other isomer and both of them had the same retention times)⁶ has been presented earlier. 2-Methyl-*exo*-2-norbornenyl acetate was obtained by heating the corresponding alcohol in a pyridine-acetic anhydride mixture.⁷ The product contained about 10 % of the *endo* acetate. The reaction media consisting of water, dioxane

* Part VII, see Ref. 5.

(purified),⁸ and perchloric acid (1.00 mol dm⁻³) were prepared by weighing the components.

The gas-chromatographic methods used for measuring the disappearance rates of the substrates and for evaluation of the formation rates of the unstable intermediate products (B) in consecutive reactions A→B→C (when A also yields other unstable products) were described earlier.¹ The effect of impurities on the disappearance rates of the substrates was eliminated by subtracting the GLC peak area of the impurity from the common peak area if they had the same retention time. The peak area of the impurity during the run was evaluated from its mol fraction in the substrate and from its reaction rate which was measured separately.

The portions of the *trans* and *cis* isomers of 1-methyl-3-nortricyclanol were measured in the intermediate products as follows. The tricyclic alcohol, obtained in the hydrolyses of the bicyclic acetate and alcohol, was separated from other components on a Perkin-Elmer F 21 preparative gas chromatograph with a Carbowax 20 M column. The alcohol was analyzed on a Perkin-Elmer Model R 10 NMR (60 MHz) spectrometer by measuring the intensities of the 1-methyl signals.⁹ Other protons, however, disturbed the analyses and the results were only approximate. More accurate results were achieved by acetylating the alcohol mixtures in acetyl chloride–N,N-dimethyl aniline (in mol ratio 1:1) at room temperature and by analyzing the acetates by GLC (retention times of the acetates were different enough when applying, e.g., a Carbowax 20 M column). The procedure was not observed to change the *cis/trans* ratio in a control experiment: III-OAc (*cis/trans* = 76/24) $\xrightarrow{\text{LiAlH}_4}$ III-OH (*cis/trans* ≈ 80/20, by NMR) $\xrightarrow{\text{Et}_2\text{O}}$ III-OAc (*cis/trans* = 76/24).

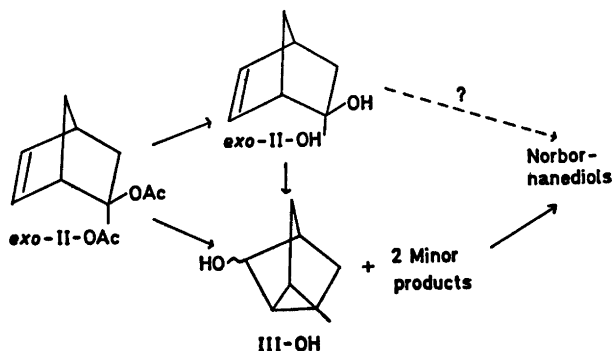
RESULTS AND DISCUSSION

2-Methyl-*exo*-2-norbornenyl acetate (*exo*-II-OAc) yields in its hydrolysis (Scheme 1) both

the unrearranged alcohol, 2-methyl-*exo*-2-norbornenol (*exo*-II-OH), and the rearranged alcohols, 1-methyl-3-nortricyclanols (*cis*- and *trans*-III-OH), and possibly two minor products (*cf.* Refs. 1 and 5). These alcohols are unstable in acidic aqueous solutions and react with the medium producing methyl-substituted norbornanediols (these were not identified).^{5,6} The formation of elimination products, diolefins, was not observed. The disappearance rates of *exo*-II-OAc and the formation and disappearance rates of *exo*-II-OH, *cis*-III-OH, and *trans*-III-OH were measured in dioxane-water mixtures containing perchloric acid, 1.00 mol dm⁻³. The hydrolysis of 1-methylcyclohexyl acetate (Pen-OAc) and 1-methylcyclohexyl acetate (Hex-OAc; the rate coefficients have been presented earlier)² was studied under the same conditions and the amount of olefins was measured in the hydrolysis products. The results are listed in Table 1.

The results of this work are in good accordance with the rate coefficients measured in Ref. 1 for two substrates ($k_a^{\text{tot}} = 18.2 \times 10^{-5} \text{ M}^{-1} \text{ s}^{-1}$ for *exo*-II-OAc and $37.9 \times 10^{-5} \text{ M}^{-1} \text{ s}^{-1}$ for Pen-OAc at 25 °C in 60 wt.% dioxane-water containing perchloric acid, 1.00 mol dm⁻³). The reaction rates depend similarly on the dioxane content of the medium in the $A_{AL}1$ hydrolyses¹ of *exo*-II-OAc, Hex-OAc, and Pen-OAc, in the $A-1$ rearrangement⁵ of *exo*-II-OH, and in the $A-S_E2$ hydration⁶ of *cis*- and *trans*-III-OH. This kind of similarity has been observed earlier in other hydrolytic reactions proceeding *via* $A-1$ and $A-S_E2$ mechanisms.¹⁰

The logarithms of the rate coefficients *versus* H_0 acidity functions of the dioxane–water



Scheme 1.

Table 1. Total disappearance rates of the substrates (k_a^{tot}) and formation rates of *exo*-II-OH from *exo*-II-OAc and of III-OH from *exo*-II-OH (k_a^f) in dioxane-water mixtures (1.00 mol dm⁻³ HClO₄) at 25 °C. Approximate amounts of olefins formed in the hydrolyses are also presented.

Substrate	Wt. % of dioxane	$k_a^{\text{tot}}/10^{-5} \text{ M}^{-1} \text{ s}^{-1}$	$k_a^f/10^{-5} \text{ M}^{-1} \text{ s}^{-1}$	k_a^f/k_a^{tot}	% olef.
<i>exo</i> -II-OAc	0.0	220 ± 3	144 ± 3	0.65	
	18.5	132 2	89.3 1.6	0.68	
	37.0	62.0 0.9	40.7 1.1	0.66	
	55.5	23.4 0.3	15.6 0.4	0.67	
	74.0	15.2 0.2	11.0 0.2	0.72	
	88.4	107 3	73.6 1.6	0.69	
	90.0	183 6	127 3	0.69	
<i>exo</i> -II-OH	0.0	13.2 ± 0.3	12.5 ± 0.2	0.95	
	18.5	6.76 0.08	6.44 0.08	0.95	
	37.0	2.91 0.06	2.70 0.08	0.93	
	55.5	1.28 0.01	0.97 0.02	0.76 ?	
	74.0	0.776 0.010	0.713 0.006	0.92	
	88.4	7.21 0.10	7.24 0.12	1.00	
	90.0	15.0 0.3	12.8 0.2	0.85	
	92.0	55.9 0.7			
	93.0	122 2			
	<i>cis</i> -III-OH	0.0	1.27 ± 0.02		
18.5		0.653 0.009			
37.0		0.312 0.007			
55.5		0.129 0.001			
74.0		0.0743 0.0008			
90.0		0.412 0.005			
<i>trans</i> -III-OH	0.0	1.77 ± 0.08			
	18.5	0.864 0.012			
	37.0	0.389 0.009			
	55.5	0.162 0.004			
	74.0	0.0946 0.0018			
	90.0	0.531 0.008			
Pen-OAc	0.0	439 ± 12			8
	18.5	205 4			7
	37.0	99.5 1.6			19
	55.5	42.5 0.9			23
	74.0	27.7 0.6			28
	90.0	450 9			29
Hex-OAc ^a	0.0	65.7 ± 1.3			4
	10.0	43.1 0.8			10
	20.0	23.5 0.5			12
	40.0	9.22 0.05			20
	60.0	3.65 0.06			33
	79.2	3.73 0.06			50
	89.1	38.5 0.6			68

^a The rate coefficients have been presented in Ref. 2.

Table 2. Slopes and intercepts for the plots of $\log k_a^{\text{tot}}$ vs. H_0 and $(\log k_a^{\text{tot}} + H_0)$ vs. H_0 for the hydrolyses of the substrates in dioxane–water mixtures (0–55.5 wt. % of dioxane, 1.00 mol dm⁻³ HClO₄) at 25 °C.

Substrate	– slope for $\log k_a^{\text{tot}}$ vs. H_0	– slope for $(\log k_a^{\text{tot}} + H_0)$ vs. H_0	– intercept
<i>exo</i> -II-OAc	1.08 ± 0.11	0.08 ± 0.11	2.84 ± 0.04
<i>exo</i> -II-OH	1.14 0.04	0.14 0.04	4.11 0.02
<i>cis</i> -III-OH	1.10 0.05	0.10 0.05	5.12 0.02
<i>trans</i> -III-OH	1.15 0.04	0.15 0.04	4.99 0.01
Pen-OAc	1.12 0.03	0.12 0.03	2.60 0.01

mixtures and the terms $(\log k_a + H_0)$ versus H_0 ¹¹ give fairly straight lines with parameters presented in Table 2 (H_0 functions for dioxane contents of 0–60 wt. % are interpolated linearly from those presented by Paul and Long).¹² The slopes are very similar for all three types of reactions studied and do not give information about the classical or non-classical characters of the transition states (cf. Ref. 2). The H_0 range employed is, however, quite narrow. (The H_0 functions have also been determined for mixtures richer in dioxane, but they are greatly scattered.)¹³

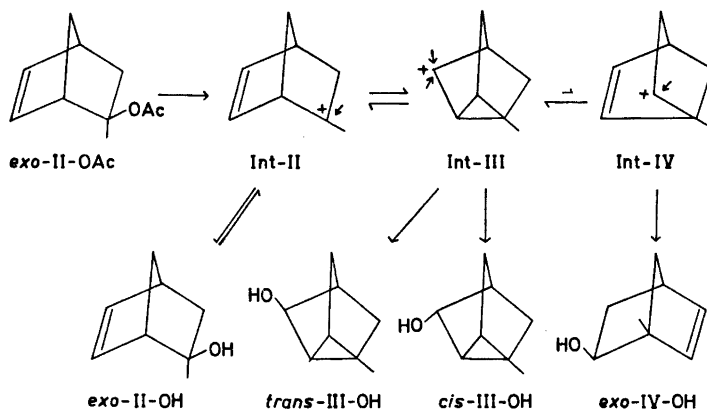
More information about the characters of the transition states and intermediates in the hydrolysis of *exo*-II-OAc and *exo*-II-OH were achieved by examination of their intermediate products. *Exo*-II-OAc produces 65–72 % (the percentage of *exo*-II-OH = $100k_a^f/k_a^{\text{tot}}$) of the unrearranged alcohol, *exo*-II-OH, the portion of which obviously does not depend on the dioxane content (Table 1). The remainder consists of the rearranged alcohols, III-OH, and possibly of two unknown minor products. *exo*-II-OH yields 93 ± 2 % of III-OH and two minor products; neither does the ratio of these products change with changing dioxane content. Analysis of the isomeric ratios of III-OH in the products yielded by *exo*-II-OAc and *exo*-II-OH (Table 3) gives interesting results: the *cis*-III-OH/*trans*-III-OH ratios are about 7/93 in solutions consisting of 0 and 55.5 % dioxane, but are distinctly larger in 95.6 % dioxane. 2-Methyl-*endo*-2-norbornenyl acetate (*endo*-II-OAc) also produces mainly *trans*-III-OH in 95.6 % dioxane (Table 3; the *cis*/*trans* ratio is probably still smaller than the observed ca. 14/86 in solutions richer in water; cf. *exo*-II-OAc). In order to check that the ratios are not affected by equilibration between *cis*-

and *trans*-III-OH, two different III-OH mixtures were submitted to similar treatment (Table 3). Marked isomerization could be seen only in 95.6 % dioxane during the reaction times employed for the bicyclic substrates. *trans*-III-OH hydrates about 30 % faster than *cis*-III-OH (Table 1), which decreases the apparent portion of the *trans* isomer in the tricyclic products. The results presented in Table 3 are not corrected with regard to these differences in the disappearance rates, but they are the observed ratios when the concentration of III-OH is approximately at its maximum.

Table 3. Amount of the *cis* isomer in 1-methyl-3-nortricyclanolols (III-OH) produced in the hydrolyses of the substrates in dioxane–water mixtures (1.00 mol dm⁻³ HClO₄) at 25 °C.

Substrate	Reaction time/h	Wt. % of dioxane	% of <i>cis</i> isomer
<i>exo</i> -II-OAc	4.3	0.0	6
	26	55.5	7
	0.2	95.6	11
<i>endo</i> -II-OAc ^a	0.1	95.6	ca. 14
<i>exo</i> -II-OH	5	0.0	5
	64	55.5	8
	3	95.6	37
III-OH (<i>cis</i> / <i>trans</i> = 76/24)	4.5	0.0	81
	3	95.6	65
	0.2	95.6	78
III-OH (<i>cis</i> / <i>trans</i> = 2/98 ^b)	0.6	0.0	7

^a 45 °C, NMR analysis. ^b 75 °C, 0.1 M HClO₄ (the reaction rates under these conditions are approximately similar to those in 1.00 M HClO₄ at 48 °C).

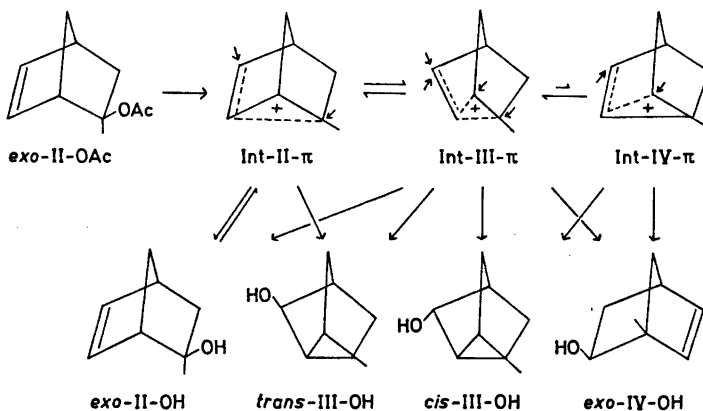


Scheme 2.

The monocyclic esters, 1-methylcyclopentyl acetate (Pen-OAc) and 1-methylcyclohexyl acetate (Hex-OAc), produce in their hydrolysis corresponding alcohols and *exo*-olefins (*i.e.* methylenecycloalkanes, by NMR), the ratios of which change fairly regularly with changing dioxane content of the medium: the apparent olefin portion increases with decreasing water concentration. (The percentages of the olefins expressed in Table 1 are only approximate averages during the two first half-lives of the reactions. Equilibration between the alcohols and the olefins was not eliminated and decomposition of the alcohols and acetates occurred slightly in GLC analyses yielding the olefins mentioned; but these effects cannot be very marked.) The increase of the olefinic portion in the products with increasing dioxane content indicates a decrease of solvent nucleophilicity, which makes the lifetime of the intermediate carbonium ions

longer in solutions richer in dioxane, thus giving time for proton elimination.

The decrease of solvent nucleophilicity has, however, no obvious effect on the *exo*-II-OH/III-OH ratio (Table 1). This eliminates the possibility that the reaction intermediate would consist of slowly (as compared with solvent attack) equilibrating classical carbocations, (Int-II, Int-III, and Int-IV in Scheme 2). If the equilibrium between the ions takes place much faster than the attack of water, occurrence of the classical carbocations is, however, possible from this point of view. The occurrence of the secondary cation, Int-IV, does not seem very probable beside the more stable tertiary cation, Int-II. The formation of *exo*-II-OH and III-OH can also take place *via* bridged homoallylic carbocations (Int-II- π , Int-III- π , and Int-IV- π in Scheme 3; geometric structures closer to norbornene than nortricyclane are assumed for the first and last and



Scheme 3.

a structure closer to nortricyclane than norbornene for the middle). The *exo*-II-OH/III-OH ratio depends on the energies of the transition states yielding the rearranged and unrearranged products.³ According to the results of this work (Table 1), the difference between the free energies is slight (*ca.* 2 kJ mol⁻¹; it is supposed that no equilibration of the products occurs). Hence, the carbocation produces also the substrate itself in the hydrolysis of *exo*-II-OH, which retards its reaction as compared with *exo*-II-OAc.

The attack of a water molecule at C(3) of intermediates Int-III and Int-III- π can take place from two directions, *cis* and *trans*. A factor, which can control the ratio of these attacks, is the methyl group, which has a steric crowding effect on the transition state of the *cis* attack. However, this effect seems very slight, because the LiAlH₄ reduction of 1-methyl-3-nortricyclanone produces *trans*- and *cis*-III-OH (*cis* and *trans* attacks, respectively) in the ratio 46:54,⁷ and in the reduction with LiAlH(OCH₃)₂, the ratio is 41:59 (performed in dry ether at 0 °C). The shielding effect of the departing acetic acid or water molecule cannot be significant either, because the departure and water attack occur on opposite sides of the moiety. Thus intermediates Int-III and Int-III- π would probably yield *cis*- and *trans*-III-OH in the approximate 1:1 ratio, which differs markedly from the observed ratio *ca.* 7/93 in 0 and 55.5 % dioxane. This fact eliminates the possibility of the rapidly equilibrating classical carbocations to yield the products in the proper ratio.

The intermediate Int-IV- π is probably also unstable as compared with Int-II- π since it requires a delocalization of the positive charge on the secondary carbon, but prevents its delocalization on the tertiary carbon. Besides, the formation of 1-methyl-*exo*-2-norbornenol (*exo*-IV-OH in Scheme 3) over *exo*-II-OH and *cis*-III-OH over *trans*-III-OH would be preferred. Two unidentified minor GLC peaks were detected in the hydrolysis of *exo*-II-OH, but their portion must be smaller than 10 % evaluated on the basis of the differences between the disappearance rates of *exo*-II-OH and the formation rates of III-OH in Table 1. Hence, the only dominating carbocation is evidently Int-II- π , which also explains well

the *cis/trans* ratio observed: much of the norbornene geometric structure remains in this cation and therefore the *exo* attack (= *trans* attack), of C(3) is more probable than the *endo* attack (= *cis* attack), but the ratio of *exo/endo* attacks may be smaller than in the cases of norbornane and norbornene skeletons.^{3,14}

The larger *cis/trans* ratios in the products of the hydrolyses of *exo*-II-OAc and *exo*-II-OH in 95.6 % dioxane than in 0 or 55.5 % dioxanes are probably partly due to equilibration of the tricyclic alcohols (Table 3), but they may be partly due to the occurrence of carbocations other than Int-II- π . This is made possible by the low nucleophilicity of the medium rich in dioxane (see above), which lengthens the lifetime of the cations and allows the isomerization of Int-II- π to other intermediates (*e.g.* *endo*-II-OH yields *trans*- and *cis*-III-OCHO in the ratio 66/33 in formic acid).⁷

In the product analysis of the solvolysis reactions of the secondary 2-norbornenyl esters (labelled properly by ³H or ¹⁴C), attention has been paid to the bicyclic compounds, which form the minority of the solvolysis products, whereas analysis of the majority of the solvolysis products, *i.e.* the tricyclic compounds, has mostly been omitted.¹⁵ However, mass spectrometric and NMR analyses have recently been performed for 3-nortricycyl acetate-*d* produced by acetolysis (125 ± 5 °C, 48 h) of 2-deuterio-*endo*-2-norbornenyl brosylate.¹⁶ The results suggest an approximately fifty-fifty attack from the "*exo*" and "*endo*" sides of the intermediate carbocation. Unfortunately, a possible equilibration of the *cis* and *trans* isomers of 3-nortricycyl acetate-*d* during the long treatment in refluxing acetic acid has, however, not been investigated.

The results of this work are in agreement with those of Ref. 1. The latter imply the occurrence of π participation in the transition state of the acid-catalyzed hydrolysis of 2-methyl-*exo*-2-norbornenyl acetate and the former suggest the occurrence of π participation in the intermediate (and evidently in the transition state of the product-yielding step) in the hydrolyses of both the *exo* acetate and the corresponding alcohol. Thus, the π participation of the homoallylic double bond causes both the increase of reaction rate and the

formation of rearranged products (*cf.* Brown *et al.*).⁴ The *exo/endo* rate ratios seem, however, to have marked individual differences, and hence they cannot be used as such to separate classical and nonclassical mechanisms.

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