voltage from 4 to 8 kV while the magnetic and electrostatic fields were kept constant at the values for the transmission of species having 4 keV of translational energy.

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Stereochemical Effects in the Gas-Phase Pinacol Rearrangement of *cis*- and *trans*-1,2-Dimethylcyclopentane-1,2-diol

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Abstract: The pinacol rearrangement of *cis*- and *trans*-1,2-dimethylcyclopentane-1,2-diol, promoted by the gaseous Brønsted acids D_3^+, $CH_5^+/C_2H_5^+$, and t-$C_4H_9^+$, was studied by mass spectrometric and radiolytic methods. Dehydration of the protonated substate is rate limiting, and competitive experiments with pinacol, carried out at high pressure (760 torr), showed that the cis rearranges more rapidly than the trans isomer, indicating participation of the migrating methyl group to the leaving water molecule. The results are compared with those concerning the same substrates in solution, where no evidence of anchimeric assistance was found.

The impressive number of studies in solution regarding the pinacol rearrangement rendered it a classic in any organic chemistry textbook. The interpretation of its mechanism, however, is complicated by the interference of undesired competitive pathways promoted by the rather drastic conditions required, e.g., strong-acid catalysis in protic solvents.[1] Such problems have been clearly enumerated,[2] and, in particular, the direct observation of a bona fide steric effect in pinacol rearrangement seemed questionable,[3] under the experimental conditions prevailing in solution.

Mass-analyzed ion kinetic energy (MIKES) and collision-induced dissociation (CID) spectrometry showed that the ions produced by water loss from protonated pinacol rearrange to the protonated pinacolone structure in the gas phase,[4] and allowed the study of related acid-catalyzed rearrangements in the chemical ionization (CI) source of a mass spectrometer.[5]

Occurrence of the gas-phase pinacol rearrangement at atmospheric pressure was also indepedently demonstrated by radiolytic methods,[6] via the actual isolation and structural characterization of the neutral end products.

In this study, a combination of radiolytic and mass spectrometric techniques was applied to provide direct evidence of stereochemical effects in the course of the pinacol rearrangement of isomeric 1,2-dimethylcyclopentane-1,2-diols; the reactions were carried out in the gas phase under experimental conditions where the factors hampering the interpretation of solution data (cis–trans isomerization, solvent interactions, etc.) are largely eliminated.

cis- and *trans*-1,2-cyclopentanediols were used as the substrates in the present experiments for the following reasons: (i) their symmetry makes protonation on either of the oxygen atoms perfectly equivalent; (ii) the presence of the five-membered ring establishes a definite steric relationship between the migrating methyl group and the leaving water molecule, and allows comparison with related rearrangements occurring in freely rotating glycols, such as the pinacol itself; (iii) the system has been independently studied in solution,[7-9] where the results strongly depend upon the experimental conditions; and (iv) under suitable conditions, the gas-phase reaction of interest is not complicated by other undesired processes.

Experimental Section

Materials. Hydrogen, deuterium, methane, isobutane, oxygen, and trimethylamine were high-purity gases from Matheson Co., used without further purification. Tetramethylene glycol and methyl *tert*-butyl ketone were chemicals from Fluka A.G. 1,2-Dimethylcyclopentene, used as starting material for the synthesis of the substrates, was prepared by dehydration of 1,2-dimethylcyclopentanol (K & K) with phosphoric acid[10] and purified by distillation at 104 °C, 760 torr.

cis-1,2-Dimethyl-1,2-cyclopentanediol (*cis*-**1**) was synthesized from the olefin and osmium tetroxide;[11] after distillation, the product was further purified by several successive crystallizations from ethyl acetate at −60 °C (mp 24 °C; bp 92 °C at 10 torr).

trans-1,2-Dimethyl-1,2-cyclopentanediol (*trans*-**1**) was prepared by addition of freshly distilled 1,2-dimethylcyclopentene on peroxyformic acid;[12] the crude glycol was purified by treatment with periodic acid and recrystallizations from benzene–cyclohexane (mp 105 °C). 2,2-Dimethylcyclopentanone (**2**) was prepared by the method of Wilcox and Mesirov.[13]

All the substrates and products were further purified by preparative GLC on the same columns employed for the analysis of products. Their final purity, as checked by GLC, exceeded 99.9 mol %.

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Table I. CID/MIKE Spectra[a] of the m/z 113 Ions from the Protonation of 2,2-Dimethylcyclopentanone (**2**) or the Dehydration of Protonated *cis*- and *trans*-1,2-Dimethyl-1,2-cyclopentanediol (**1**), Using CH_4 or i-C_4H_{10} as Reactant Gases

	CH_4 CI			i-C_4H_{10} CI		
m/z	**2**	*cis*-**1**	*trans*-**1**	**2**	*cis*-**1**	*trans*-**1**
97	17.5	16.6	17.3	25.4	23.8	23.4
83	2.6	3.0	2.3	2.7	3.2	2.8
77	2.2	2.1	2.3	2.7	2.7	2.5
71	4.5	5.2	4.1	2.2	2.7	3.4
69	10.5	11.7	11.2	9.0	10.6	10.1
67	4.0	4.3	3.9	5.0	4.9	4.5
57	4.0	3.9	4.0	3.5	3.6	3.5
55	19.2	18.3	19.9	16.3	16.5	17.1
53	4.3	4.4	4.2	4.5	4.7	4.5
41	15.3	14.0	14.6	13.5	12.7	13.5
39	7.9	7.9	7.9	8.5	7.8	8.3
29	3.9	4.5	4.3	3.0	2.9	2.9
27	3.9	4.2	4.0	3.7	4.1	3.6

[a] Relative intensity as per cent of total fragment ion abundances, except for ions m/z 95 and 43, which are also formed by metastable ion decomposition. The data are the average of at least three independent runs, each representing the accumulation of 30 consecutive scans. RSD = ~15%.

Radiolytic Experiments. The gaseous reaction mixtures were prepared by conventional techniques, using greaseless vacuum lines. The reagents and the additives were introduced into carefully evacuated and outgassed 500-mL Pyrex bulbs, which were eventually filled with the appropriate bulk gas (D_2, CH_4, isobutane) and sealed off. The irradiations were carried out at 37.5 °C in a 220 Gammacell from Nuclear Canada Ltd., to a total dose of 2×10^4 Gy at a dose rate of ca. 10^4 Gy h^{-1}, as determined by a Fricke dosimeter.

The analyses of the irradiated samples were carried out using a Hewlett-Packard model 5730A gas chromatograph, equipped with a FID unit on either a 8-ft × 0.25 in. glass column packed with FFAP (5%) on Chromosorb G AW-DMCS (80–100 mesh), operated at 60–210 °C (rate 8 °C min^{-1}), or a 50-m long, 0.31-mm i.d. fused silica capillary column coated with Carbowax 20M operated at 70–190 °C (4 °C min^{-1}). The identity of products was deduced by comparison of the elution times of the corresponding peaks with those of authentic samples and confirmed by GLC/MS, using a Hewlett-Packard Model 5982A mass spectrometer. The yields of the products were deduced from the areas of the corresponding elution peaks, measured with a Hewlett-Packard 3390A integrator, using individual calibration factors.

Mass Spectrometric Measurements. The MIKE and the CID spectra were recorded on a ZAB-2F spectrometer from VG-Micromass Ltd., fitted with a combined EI/CI ion source. Unless otherwise specified, typical source parameters were: 0.5 mA, emission current; 100 eV, electron energy; 0 V, repeller voltage; 150 °C, source temperature; 0.5 mbar, reactant gas pressure (CH_4 or i-C_4H_{10}), as directly measured with a MKS Baratron Type 221-A manometer. The CID spectra were obtained by filling the gas cell located in the second field-free region (FFR) of the reverse-geometry instrument with the collision gas (He) until the parent ion intensity was reduced to 30% of its original value, and by scanning the electric-sector analyzer. The instrument was tuned to a mass resolution greater than 2000 (10% valley definition) at the first collector and to an energy resolution of 5000 fwhm, at an accelerating voltage of a 8 kV. The spectra were collected by a VG-2350 Data System, and represent the average of at least 30 consecutive scans.

Results

Mass Spectrometric Measurements. Both *cis*-**1** and *trans*-**1** display relatively intense m/z 113 peaks in the CH_4 and i-C_4H_{10} CI spectra, corresponding to ions generated in the source of the mass spectrometer by water loss from the protonated substrates. Under the same experimental conditions, ionic species with the same m/z ratio are also formed by direct proton transfer to 2,2-dimethylcyclopentanone (**2**). Such ions, isolated with the magnetic sector, may undergo unimolecular metastable decomposition in the second field-free region (FFR) of the instrument, producing fragments at m/z 95 and 43, whose relative intensities are respectively: *cis*-**1**, CH_4: 100, 13.4 (i-C_4H_{10}: 100, 8.3); *trans*-**1**, CH_4: 100, 12.2 (i-C_4H_{10}: 100, 7.9); **2**, CH_4: 100, 13.8 (i-C_4H_{10}: 100, 8.7).

When He is introduced in the gas cell located in the second FFR, the collision-induced dissociation of m/z 113 ions gives the CID spectra reported in Table I, where the peaks at m/z 95 and 43 are excluded, owing to possible unimolecular contributions to their intensities.

Table II. Correlation Coefficients of CID/MIKE Spectra of the m/z 113

		CH_4			i-C_4H_{10}	
		cis-**1**	*trans*-**1**	**2**	*cis*-**1**	*trans*-**1**
i-C_4H_{10}	*cis*-**1**	0.935	0.934	0.940		
	trans-**1**	0.951	0.950	0.957	0.997	
	2	0.916	0.917	0.927	0.996	0.994
CH_4	*cis*-**1**		0.997	0.996		
	trans-**1**			0.998		

Table III. Products from the Protonation of *cis*- and *trans*-1,2-Dimethylcyclopentane-1,2-diol by Gaseous Acids

system composition (torr)[a]			gaseous acid	products absolute yield (G_M)[b]
bulk gas	$N(CH_3)_3$	substrate		
D_2, 760		*cis*-**1**, 0.10	D_3^+	**2**, 1.2
D_2, 760	7	*cis*-**1**, 0.13	D_3^+	**2**, 0.2
D_2, 100		*cis*-**1**, 0.12	D_3^+	**2**, 2.1
D_2, 760		*trans*-**1**, 0.11	D_3^+	**2**, 0.8
D_2, 760	7	*trans*-**1**, 0.10	D_3^+	**2**, 0.05
D_2, 100		*trans*-**1**, 0.12	D_3^+	**2**, 1.2
CH_4, 760		*cis*-**1**, 0.09	CH_5^+, $C_2H_5^+$	**2**, 0.9
CH_4, 760	7	*cis*-**1**, 0.14	CH_5^+, $C_2H_5^+$	**2**, 0.1
CH_4, 100		*cis*-**1**, 0.13	CH_5^+, $C_2H_5^+$	**2**, 1.3
CH_4, 760		*trans*-**1**, 0.10	CH_5^+, $C_2H_5^+$	**2**, 0.4
CH_4, 760	7	*trans*-**1**, 0.09	CH_5^+, $C_2H_5^+$	**2**, 0.1
CH_4, 100		*trans*-**1**, 0.12	CH_5^+, $C_2H_5^+$	**2**, 0.8
neo-C_5H_{12}, 760		*cis*-**1**, 0.13	t-$C_4H_9^+$	**2**, 0.02[c] + other products
neo-C_5H_{12}, 760		*trans*-**1**, 0.10	t-$C_4H_9^+$	**2**, 0.007[c] + other products

[a] O_2 (5 torr) was introduced in all systems as radicals scavanger. [b] Number of molecules formed per 100 eV of absorbed energy. Standard deviation of the yields ca. 10%. See text. [c] Other products are formed, e.g., from the alkylation of substrates and the addition of t-$C_4H_9^+$ to isobutene, a major product from the radiolysis.

The correlation coefficients "r" for the linear regression of the intensities of each spectrum on all the others, taken as an estimate of similarity of the spectra,[14] are summarized in Table II.[15]

Since spectra of the m/z 113 ions from the same precursor, collected in different days with the same setting of the instrumental parameters, gave values exceeding 0.97 for all the substrates, the spectra of *cis*-**1**, *trans*-**1**, and **2** from either isobutane or methane CI are indistinguishable. As shown in Table II, slightly lower values of "r" characterize couples of spectra obtained from the same precursors, but employing different reagent gases, possibly owing to internal energy effects on the m/z 113 ions formed by the differently exoergic protonation by t-$C_4H_9^+$ or $C_nH_5^+$ (n = 1, 2) acids. Nevertheless, the correlation coefficients for spectra from the same substrate are very close to those from different ones, pointing to a common ionic structure in all cases.

Radiolytic Experiments. The composition of the irradiated system and the yields of the neutral end products obtained following protonation of the substrates with gaseous Brønsted acids, generated according to well-established radiolytic techniques,[16,17] are given in Table III.

The ionic character of the reaction is ensured by the presence of O_2, an effective radical scavenger, and by the observed strong

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(15) r was calculated according to the standard formulas; see: *CRC Standard Mathematical Tables*, 27th ed.; Beyer, N. H., Ed.; CRC Press: Boca Raton, 1984; p 498.

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decrease of the yields when a few torr of $N(CH_3)_3$, an efficient interceptor of gaseous acids, is added to the system.[18]

The experimental G_M values reported (defined as the number of molecules formed per 100 eV absorbed energy) are reproducible within ±5%, for a given system composition and radiation dose. It must be pointed out, however, that, owing to the many sources of uncertainty associated with dosimetry, and with the accumulation of radiolytic products whose effects are hardly predictable, these values can be only regarded as a crude estimate (ca. ±30%) when compared with the known formation yields of the gaseous acids under similar conditions. Nevertheless, for the purpose of the present work, the results clearly indicate that the reaction is very clean and efficient when D_2 or CH_4 is used as the reagent gas; in fact, the absolute yield of **2** from *cis*-**1** and from *trans*-**1** respectively accounts for ca. 40 and 25% of the D_3^+ and 31 and 15% of the $C_nH_5^+$ (n = 1, 2) ions formed in the system at 760 torr.[19] At a lower pressure (100 torr), the yields are even higher, approaching ca. 70 and 41% in D_2 and 47 and 29% in CH_4.

No appreciable amount of any other product from the substrates was recovered. On the other hand, when *tert*-butyl cations from the radiolysis of neopentane were used as the acid, very low yields (ca. 0.7% for *cis*-**1** and 0.2% for *trans*-**1**) resulted, and other products were formed in addition to **2**.[20] When the irradiation of CH_4 (D_2)/*cis*-**1** or CH_4 (D_2)/*trans*-**1** mixtures was carried out in the presence of a few torr of H_2O, no cis–trans isomerization of the substrates was observed in competition with the rearrangement to **2**. Furthermore, GLC/MS analysis of the irradiation products showed no deuterium incorporation into the ketone from all reactions with D_3^+ ions.

The relative reactivity of the 1,2-dimethylcyclopentane-1,2-diol isomers was measured by competition experiments of each substrate vs. pinacol, taken as a standard, since its ability to rearrange in the dilute gas state was already demonstrated in a preceding study.[6] The composition of the radiolytic system and the relative yields of the products from the reactions promoted by D_3^+ and $C_nH_5^+$ (n = 1, 2) acids are summarized in Table IV.

Discussion

Both under the CI conditions prevailing in the source of the mass spectrometer and in the radiolytic systems, at much higher pressures, the ionization of the reactant gases yields eventually gaseous Brønsted acids, i.e., D_3^+ from D_2, CH_5^+ and $C_2H_5^+$ from CH_4, and $t\text{-}C_4H_9^+$ from $i\text{-}C_4H_{10}$ or $neo\text{-}C_5H_{12}$,[21,22] which all undergo exoergic proton transfer to glycols **1** and to pinacol (M).

$$AH^+ + M \rightarrow MH^+ + A \qquad (1)$$

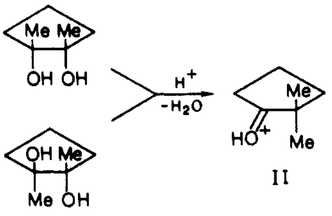
$$A = D_2;\ CH_4,\ C_2H_4;\ i\text{-}C_4H_8$$

Although experimental values of the gas-phase basicities (GB) of the substrates are not available, the standard free energy changes $\Delta G°$ associated with reaction 1 can roughly be estimated from the GB values of the conjugate bases A of the acids[23] and those for unsubstituted *cis*- and *trans*-1,2-cyclopentanediol and 2,3-butanediol.[24] The expected basicity order of the substrates is *cis*-**1** ≥ pinacol ≥ *trans*-**1**, and $-\Delta G°$ for reaction 1 should approximately fall for all the diols in the range 95–98 for D_3^+, 65–68 and 34–37, respectively, for CH_5^+ and $C_2H_5^+$ and 3–5 kcal mol^{-1} for $t\text{-}C_4H_9^+$.[25]

In agreement with the CI pattern of other substituted glycols,[5] the mass spectra contain no significant MH^+ ions, which undergo dehydration before leaving the ion source (~10^{-6} s), even if formed from $t\text{-}C_4H_9^+$, the mildest gaseous acid employed.

It should be noted that dehydration is expected to be easier under CI conditions than in radiolytic experiments, owing to the presence of excited $t\text{-}C_4H_9^+$ at the lower pressure, and to the higher temperature (150 °C) of the ion source.

Addressing the crucial point of assigning the structure to the $[MH - H_2O]^+$ ions from diols **1**, one can move from the strong evidence arising from the demonstrated identity of their CID spectra with that of the MH^+ ion from **2**. In order to prove their structural identity, it remains to show that any m/z 113 ion from the diols, which had not undergone 1,2-methyl shift, would give a spectrum different from protonated **2** (II). Indeed, the actual isolation of **2** as the only significant neutral product formed from **1** in the radiolytic experiments, allows us to safely assign the structure of protonated 2,2-dimethylcyclopentanone to the m/z 113 ions.[26]



II

(2)

Such results, taken in conjunction with the mass spectrometric experiments, demonstrate that all the ions from the proton-induced dehydration of *cis*- and *trans*-1,2-cyclopentanediol must have undergone pinacol-like rearrangement within 5 × 10^{-6} s from their formation, independently of the nature of the gaseous acid employed.

The conditions prevailing in the radiolytic experiments, i.e., much higher pressures and lower temperatures, ensure efficient thermalization of the reagent(s) and, in addition, allow the observation of reaction steps occurring in a time interval up to two orders of magnitude shorter than that typical of mass spectrometric experiments, depending on the system composition.

The extremely low yields of **2** from the rearrangment of *cis*- and *trans*-**1**, induced by radiolytically formed $t\text{-}C_4H_9^+$ ions (Table III) are in agreement with the low $-\Delta G°$ value predicted for the protonation step, and point to an energy barrier for the overall process. This is confirmed by the higher yields obtained when the ionic intermediates are formed with higher internal energy, e.g., by using stronger Brønsted acids (D_3^+ or $C_nH_5^+$) and/or when the efficiency of collisional quenching is reduced by lowering the pressure of the system to 100 torr.

Under the same experimental conditions, *trans*-**1** gives invariably lower absolute yields than the cis isomer, without formation of byproducts. Since the overall process is not reversible, a fraction of some ionic intermediates should revert to the substrate before undergoing 1,2-methyl shift. The protonated glycol is a likely candidate, which can be collisionally stabilized under the conditions prevailing in the radiolytic experiments and undergo deprotonation prior to dehydration. Competitive experiments (Table IV) confirm this view, showing that addition of $N(CH_3)_3$ inhibits rearrangement of *trans*-**1** to a greater extent than that of pinacol and of *cis*-**1**.

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(18) (a) Attinà, M.; Cacace, F; Giacomello, P. *J. Am. Chem. Soc.*, **1980**, *102*, 4768. (b) Attinà, M.; Cacace, F.; Ciranni, G.; Giacomello, P. *J. Chem. Soc., Chem. Commun.* **1978**, 938. (c) Attinà, M.; Cacace, F.; Giacomello, P.; Speranza M. *J. Am. Chem. Soc.* **1980**, *102*, 6896. (d) Fornarini, S.; Speranza, M.; Attinà, M.; Cacace, F.; Giacomello, P. *Ibid.* **1984**, *106*, 2498.

(19) $G(CH_5^+)$ = 1.9 ± 0.2 and $G(C_2H_5^+)$ = 0.9 ± 0.2 according to: Ausloos, P.; Lias, S. G.; Gorden, R., Jr. *J. Chem. Phys.* **1963**, *39*, 3341. $G(H_3^+)$ = 3 according to: Weiss, J.; Bernstein, W. *Radiat. Res* **1957**, *6*, 603.

(20) $G(t\text{-}C_4H_9^+) \simeq 3.2$ according to ref 16b; Lias, S. G.; Ausloos, P. *J. Chem. Phys.*, **1965**, *43*, 2748; Lias, S. G.; Rebbert, R. E.; Ausloos, P. *Ibid.* **1972**, *57*, 2080.

(21) Cf. Harrison, A. G. *Chemical Ionization Mass Spectrometry*; CRC Press: Boca Raton, 1983.

(22) Cf. e.g.: (a) Cacace, F.; Giacomello, P. *J. Am. Chem. Soc.* **1973**, *95*, 5851. (b) Cacace, F.; Ciranni, G.; Giacomello, P. *J. Chem. Soc., Perkin Trans. 2* **1982**, 1373.

(23) Cf. Lias, S. G.; Liebman, J. F.; Levin, R. D. *J. Phys. Chem. Ref. Data* **1984**, *13*, 695.

(24) Guenat, C.; Houriet, R.; Stahl, D.; Winkler, J. *Helv. Chim. Acta* **1985**, *68*, 1647. CAD data were taken and brought to the same scale of ref 23.

(25) The estimates refer to model compounds with H instead of CH_3 as substituents on the carbons bearing the OH groups: the true $-\Delta G°$ values might be a little bit higher, considering the basicity difference between secondary and tertiary alcohols, e.g., the Δ(GB) between t-BuOH and i-PrOH is +2.5 kcal mol^{-1}. However, the correction is well within the error limits of the data used and does not influence the interpretation of our results.

(26) Another conceivable structure for the m/z 113 ions would be that of a protonated epoxide. However, the epoxide itself is unstable under the conditions employed and its formation from the ketone appears very unlikely.

Table IV. Competitive Acid-Catalyzed Rearrangement of 1,2-Dimethylcyclopentane-1,2-diols and Pinacol in the Gas Phase

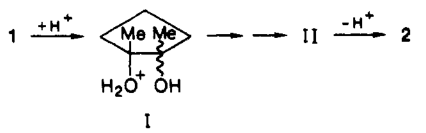
system composition (torr)[a]				acid	products yield (%)[b]		reactivity ratio[c]
cis-**1**	*trans*-**1**	pinacol	$N(CH_3)_3$		**2**	pinacone	
0.11		0.54		D_3^+	18	82	1.0
0.11		0.56	4	D_3^+	15	85	0.9
	0.10	0.49		D_3^+	17	83	1.0
	0.11	0.50	4	D_3^+	7	93	0.4
0.10		0.54		CH_5^+, $C_2H_5^+$	25	75	1.7
0.10		0.49	4	CH_5^+, $C_2H_5^+$	25	75	1.7
	0.10	0.45		CH_5^+, $C_2H_5^+$	17	83	1.0
	0.11	0.51	4	CH_5^+, $C_2H_5^+$	7	93	0.4

[a] All system contained D_2 (or CH_4), 760 torr, and O_2, 5 torr. [b] Standard deviation of data ca. 10%. [c] Calculated by correcting the rearrangement product yields ratio for the concentration of the substrates.

Since deprotonation effectively competes with dehydration, the lifetime of protonated *trans*-**1** must be comparable with the collision interval with the base in the system ($\simeq 10^{-8}-10^{-9}$ s), while the faster rearrangement of pinacol and *cis*-**1** should have taken place within that time interval.

The evidence from radiolytic results therefore strongly indicates that the protonated substrate is the only ionic intermediate surviving rearrangement long enough to be trapped in a bimolecular reaction.

Attempts to trap a possible free carbocation were unsuccessful: in fact, (i) it would be expected to undergo condensation with water, but no epimerization product was recovered when the reaction was carried out in the presence of H_2O; and (ii) if it were an intermediate, $N(CH_3)_3$ could exothermically abstract its ring proton to yield an unsaturated alcohol. The base actually failed to cause any other effects besides lowering the yields by interception of the primary Brønsted acids and of the protonated substrate.



(3)

On one hand, therefore, the mass spectrometric results show completely rearranged $[MH-H_2O]^+$ ions after a relatively long time (5×10^{-6} s); on the other hand, the radiolysis indicates the MH^+ ion as the ionly intermediate surviving structural rearrangement as long as $10^{-8}-10^{-9}$ s in the high-pressure system.

The reactivity ratios reported in Table IV, from the experiments carried out in the absence of the base, show that when the most energetic reagent, D_3^+, is used there is no difference in the overall rates for pinacol, the cis and trans isomers, while in the case of the $CH_5^+/C_2H_5^+$ mixture from methane, *cis*-**1** appears to react 1.7-fold faster than both pinacol and *trans*-**1**.

In the first case, the internal energy of the MH^+ ions allows them to rapidly and unselectively undergo water loss, while in the second one, collisional quenching by the bulk gas may effectively interfere and prevent a fraction of the intermediates from overcoming the dehydration barrier, displaying selectivity. In this view, pinacol and *trans*-**1** appear to have a higher energy barrier than the cis epimer.

For this compound, the presence of $N(CH_3)_3$ has no effect, or at least exactly the same effect as for pinacol, on the following rearrangement to ketone. The lack of such a base effect indicates that the deprotonation rate, $k[B]$, is much lower than the one for the unimolecular rearrangement, k_R, unless this letter value is very close for *cis*-**1** and pinacol.

Comparison of the reactivity ratio, relative to pinacol, for the trans isomer, in the presence or in the absence of $N(CH_3)_3$, leads to estimate its $k_R \leq 0.66k[B]$, under steady-state approximation. Since the GB of $N(CH_3)_3$ (217.3 kcal mol^{-1})[23] largely exceeds that of the substrates, and since there is no plausible reason to expect marked differences among the proton-transfer rates from the protonated glycols, the decrease in the reactivity of the trans isomer in the presence of the base is a strong indication that its rearrangement to ketone proceeds at a slower rate than that of pinacol and *cis*-**1**.

This clearly implies participation of the methyl group in the dehydration of the last two substrates, where the migrating group already occupies or may move to, by rotation around a C–C bond, a position anti with respect to the leaving water molecule.

It is noteworthy that the influence of the stereochemistry of the diol upon the rearrangement rate is still evident in the competitive reaction promoted in the presence of $N(CH_3)_3$ by D_3^+ ions, whose highly exoergic and unselective proton transfer to the substrates can generate excited intermediates, and therefore favor rapid water loss.

As a conclusion, in the gas-phase rearrangment of the five-membered ring glycols and of pinacol the dehydration step is rate limiting and involves participation, when stereochemically allowed, by the methyl group. The higher reactivity of cis-**1** with respect to pinacol in methane cannot be justified by basicity differences between the substrates, since the acid is strong enough to level them. It is indicative, instead of a different dehydration rate, which reflects, inter alia, the more unfavorable entropy factors for the participation in pinacol.

Furthermore, the results speak against formation of free carbenium ions as intermediates, surviving at least 10^{-8} s in the system prior to undergoing rearrangement.

Comparison with Solution Results. In boiling 30% sulfuric acid cis-**1** gave good yields of **2**, but *trans*-**1** was resinified;[7] at lower temperature, −10 °C, a 20% yield of the ketone was recovered.[27] The behavior was confirmed in 3 M perchloric acid and, in addition, extensive oxygen exchange between trans diol and solvent water was observed.[8] The kinetic study assumed the loss of an hydroxyl group as rate-limiting and led to the suggestion of an A-1 mechanism, involving two distinct intermediates from the two epimers, with little or no assistance of the alkyl or hydroxyl group to bond breaking.[8] On the other hand, the rates of solvolysis of substituted *cis*-2-tosyloxycyclopentanols in acetate-buffered acetic acid indicated neighboring group participation at the secondary carbon center.[9]

The impressive number of studies carried out so far suggests that there are at least three fundamental routes for the pinacol rearrangement in solution, namely, via a carbocation, by a concerted mechanism, and via an epoxide intermediate, depending on the structure of the diol and on the reaction conditions employed.[1] Moreover, the recognition of neighboring group participation in solution is often complicated by nucleophilic solvent assistance to the leaving group.

In the gas phase, evidence for anchimeric assistance was provided by the mass spectrometric study of the fragmentation of monomethyl and monoacyl glycols.[28] Direct evidence of neighboring group participation was also provided in high-pressure protonation of vicinal halogeno alcohols, and quantitatively evaluated for the OH, Br, and Cl groups.[29-31]

The present results, obtained in a gas-phase environment ensuring collisional stabilization of the intermediates but not ap-

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preciably affected by complicating competitive pathways, are supposed to be representative of the intrinsic course of the pinacol rearrangement. The kinetic data did not allow separation of the dehydration step from the migration of the methyl group since the protonated *trans*-1,2-dimethyl-1,2-cyclopentanediol is the only intermediate surviving long enough to be trapped by a base.

The observation of a rate enhancement in the rearrangement of the cis isomer and the failure to observe any product traceable to the intermediacy of a carbenium ion strongly support a rearrangement mechanism involving participation of the methyl group to the leaving of the water molecule. This behavior appears in contrast with evidence from solution-chemistry studies of the same substrates, indicating possible stabilization of the tertiary carbenium ion by the solvent in the condensed medium.

Additional evidence for this effect is provided by the observed nucleophilic assistance of water molecules in the epimerization of the trans diol in acidic solution,[8] which is not operative in the gas phase, under the conditions of the present study.

It can also be noted that, in the absence of significant interactions with the solvent, conformational effects may play a role in the gas phase. In fact, in substituted cyclopentane, the cis epimer might exhibit higher strain than the trans one. This effect, whose magnitude is unknown in the protonated substrates but apt to be small, could contribute to accelerate the rearrangement of the cis with respect to the trans diol.[32] Further work on suitable model compounds is in progress to evaluate the point. On the other hand, a conformational effect can help explain the apparently inefficient participation of the hydroxyl group in *trans*-**1**.

In fact, a proton bridge may stabilize the ring conformation bearing the OH groups in a quasi-equatorial position at the expense of the only one suited for OH participation, namely, that having the migrating group in an antiperiplanar position with respect to the leaving water molecule.

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Registry No. *cis*-**1**, 33046-19-4; *trans*-**1**, 33046-20-7; **2**, 4541-32-6; D_3^+, 12595-96-9; CH_5^+, 15135-49-6; $C_2H_5^+$, 14936-94-8; *t*-$C_4H_9^+$, 14804-25-2; *t*-$C_4H_9CH_3$, 463-82-1; CH_4, 74-82-8; *i*-C_4H_{10}, 75-28-5; $N(CH_3)_3$, 75-50-3; D, 7782-39-0; $HOC(CH_3)_2C(CH_3)_2OH$, 76-09-5; 1,2-dimethylcyclopentene, 765-47-9.

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[32] This possibility was considered by one of the referees whose suggestion is gratefully acknowledged.

Gas-Phase Cationic Methylation of Biphenyl and Methylbiphenyls. A Mass Spectrometric and Radiolytic Study

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Abstract: Alkylation of biphenyl and methylbiphenyls by Me_2F^+ and Me_2Cl^+ ions has been studied in the gas phase by a combination of radiolytic and mass spectrometric techniques, including chemical ionization and collisionally induced dissociation spectrometry. The results, in particular, the disproportionately high extent of ortho substitution, conform to a mechanistic model envisaging, in addition to direct substitution, the preliminary formation of an electrostatically bound adduct between the symmetric, bidentate electrophile and *both* rings of the substrate. Formation of the adduct increases the local concentration of the electrophile, hence the rate of alkylation at the ortho positions of biphenyl.

As an extension of previous studies on aromatic substitution by gaseous cations,[1] we have investigated the reactivity of biphenyl and methylbiphenyls toward two typical methylating agents, Me_2F^+ and Me_2Cl^+, in the dilute gas state. It had been noted that substituents containing localized n-electron pairs on halogen, oxygen, and nitrogen atoms promote a disproportionately high extent of ortho substitution by gaseous cations. This has led to the suggestion that, in addition to direct attack, ring substitution can involve the formation of a preliminary adduct, characterized by the electrostatic interaction of the cation with the n electrons of the substituent, which increases the local concentration of the electrophile at the ortho positions, accounting for the observed regioselectivity.[2-5]

Biphenyl, a substrate containing two adjacent aromatic rings, provides a suitable model to ascertain whether an analogous preliminary interaction, involving a delocalized π system rather than a localized n-electron pair, enhances the regioselectivity of the substitution by gaseous, unsolvated cations. In this connection, it is of interest that some kind of participation of the ring not being attached has been invoked to account for the ortho orientation prevailing in certain reactions of biphenyl in solution.[6,7] Furthermore, the reactivity of biphenyl is well characterized by theoretical and semiempirical treatments,[8,9] as well as by free-energy correlations,[10] which provide useful comparison terms to

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