Conformation and Reactivity. Part 9.[1] Kinetics of the Acid- or Base-Catalysed Methanolysis of the Methyl Esters of *trans*-Decalin- or Cyclohexane-carboxylic Acid and Related Acids. The Validity of Taft's Method for the Separation of Polar, Steric, and Resonance Effects

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Rate coefficients have been measured for the acid- or base-catalysed methanolysis at several temperatures in CD_3OD of methyl *trans*- and *cis*-4-t-butylcyclohexanecarboxylate, methyl cyclohexanecarboxylate, methyl *trans*-decalin-1α-, -1β-,-2α-, and -2β-carboxylate, methyl *endo*- and *exo*-norbornane-2-carboxylate, and methyl bicyclo[2.2.2]octane-1-carboxylate and its 4-bromo-derivative. The reactions of the methyl *trans*-decalin-2-carboxylates in mixtures of CD_3OD with $(CD_3)_2SO$, C_6D_6, or D_2O were also studied. The results are discussed in relation to the influence on reactivity of steric and polar effects in the various molecular skeletons and conformers. Further examples of the anomalous behaviour of the decalin-1α-carboxylate have been found. The bearing of the results for the decalin-2-carboxylates on Taft's assumption regarding the equality of steric effects in acid- and base-catalysed ester reactions is discussed. On balance the validity of Taft's assumption is confirmed.

SEVERAL previous Parts have dealt with the kinetics of the acid-catalysed or alkaline hydrolysis of the methyl esters of *trans*-decalin- or cyclohexane-carboxylic acids and related acids in aqueous organic solvents,[2,3] or with the kinetics of the acid-catalysed esterification of the parent acids in methanol.[4]

The use of a 4-Bu^t group or a $[CH_2]_4$ bridge (*trans*-decalin system) to lock the conformation of cyclohexane compounds has been of special interest and thus the reactivity of the functional group in both the axial and the equatorial disposition has been studied. We have previously suggested [2] that this provides a means of investigating the main assumption of Taft's separation of polar, steric, and resonance effects,[5] *viz.* that in corresponding acidic and alkaline ester reactions, steric effects are the same. (Taft's analysis leads to the σ* and E_s scales of substituent constants, which are much applied in the correlation analysis of organic reactivity.[5,6]) Proper examination of this assumption requires a system in which steric effects can be varied substantially without changing polar or resonance effects. Corresponding pairs of compounds with conformations locked as indicated above, so that the functional group is axial in one compound and equatorial in the other, should give a good approximation to this condition. Some years ago we obtained results which cast doubt on the assumption of the equality of steric effects in acid-catalysed and alkaline ester hydrolysis,[2] although there were indications that Taft's assumption might be more closely fulfilled as between alkaline hydrolysis in aqueous organic solvents [3] and acid-catalysed esterification in methanol.[4]

The assumption of the equality of steric effects has also been criticised in the course of other work [6,7] and by other authors.[8,9]

We considered that the study of the methoxy exchange reactions of methyl cyclohexanecarboxylates in CD_3OD could shed light on the matter, in so far as these reactions are essentially simpler than the ester reactions normally considered. The reactions are (1) and (2). Reaction (1) (ester reacting with sodium deuteriomethoxide) is analogous to alkaline hydrolysis, whereas reaction (2) (ester reaction with deuteriomethanol, catalysed by deuterium ions) is analogous to acid-catalysed hydrolysis. These reactions have several advantages: (i) they can be studied in a one-component solvent CD_3OD or in certain mixed solvents, (ii) experimental conditions

$$RCO_2CH_3 + OCD_3^- \longrightarrow RCO_2CD_3 + OCH_3^- \quad (1)$$

$$RCO_2CH_3 + CD_3OD \xrightarrow{D^+} RCO_2CD_3 + CH_3OD \quad (2)$$

are convenient, and (iii) because the carbonyl addition intermediate is symmetrical, the observed rate coefficient, k, has a simple significance, *viz.* $k_1/2$, where k_1 is the rate coefficient for the formation of the intermediate.†

The deuterium labelling enables the exchange to be followed by ^1H n.m.r. since the ester OCH_3 signal disappears as reaction proceeds. This kinetic technique requires only very small quantities of reactants.

We have studied the exchange reactions at several temperatures in CD_3OD of methyl *trans*- and *cis*-4-t-butylcyclohexanecarboxylate, methyl cyclohexanecarboxylate, and methyl *trans*-decalin-1α-, -1β-, -2α-, and -2β-carboxylate. Methyl *trans*-decalin-4a-carboxylate was prepared *via* the acid [10] but it proved to be too unreactive for study. We have also studied methyl *endo*- or *exo*-norbornane-2-carboxylate, and methyl bicyclo[2.2.2]octane-1-carboxylate and its 4-bromo-derivative. The last system was chosen to reveal the sensitivity of each reaction to polar effects, while it was hoped that the former would constitute another system which could be used to test Taft's assumption. (As will be seen later, this hope was not realised.) The exchange reactions of the methyl *trans*-decalin-2-carboxylates in mixtures of CD_3OD with $(CD_3)_2SO$, C_6D_6, or D_2O were also studied. In CD_3OD–D_2O exchange and hydrolysis occur simultaneously, *i.e.* reactions (3) and (4) occur in

† For basic methanolysis the statement is correct as it stands, but for acidic methanolysis k_1 is the product of K for deuteronation of the ester E to give ED^+, and the rate coefficient for the attack of CD_3OD on ED^+.

addition to (1) and (2), and the observed rate coefficient is for the sum of (1) and (3) or (2) and (4).

$$RCO_2CH_3 + OD^- \longrightarrow RCO_2^- + CH_3OD \quad (3)$$

$$RCO_2CH_3 + D_2O \xrightarrow{D^+} RCO_2D + CH_3OD \quad (4)$$

We had hoped to separate exchange and hydrolysis by studying the latter in CH_3OD–D_2O but the ester CH_3 signal was obscured by the large solvent CH_3 peak.

EXPERIMENTAL

Methyl cyclohexanecarboxylate, methyl *cis*- and *trans*-4-t-butylcyclohexanecarboxylate,[2] methyl *trans*-decalin-1α-, -1β-, -2α-, and -2β-carboxylate,[3] and methyl bicyclo[2.2.2]-octane-1-carboxylate, and methyl 4-bromobicyclo[2.2.2]-octane-1-carboxylate [11] were prepared as described previously. Methyl *endo*-norbornane-2-carboxylate was prepared from the acid [12] by esterification with diazomethane; the *exo*-ester was prepared from the *endo*-ester by equilibration with sodium methoxide in methanol.[13] All the esters gave single peaks in g.l.c. analysis.

Toluene-*p*-sulphonic acid monohydrate was stored *in vacuo* over $CaCl_2$ and silica gel. The deuteriated solvents, which were used without purification, were from Prochem Ltd; CD_3OD 99.5% D, $(CD_3)_2SO$ 99.8% D, C_6D_6 99.5% D, D_2O 99.8% D.

As far as possible, all materials were stored and manipulated in a nitrogen atmosphere in a dry-box (desiccants, P_2O_5 and silica gel).

N.m.r. spectra were recorded at 100 MHz with a JEOL 4H-100 spectrometer. Wilmad Glass Company microtubes (cat. no. 508-CP) with elongated cylindrical cavities were fitted with a brass thread and individually matched brass screw caps, each of which contained a gas-tight silicone-rubber sealing disc (bottom of tube to bottom of cavity 15—16 mm, length of cavity 8 mm, volume of cavity 150 μl, total length of tube 170 mm, internal diameter of main stem 2 mm).

Kinetic Procedure for Acid-catalysed Methanolyses.—Toluene-*p*-sulphonic acid monohydrate (*ca.* 0.0200 g) was weighed accurately into a calibrated graduated flask (volume *ca.* 1.600 ml) and a small amount of CD_3OD [containing 1,2,4,5-tetramethylbenzene as a reference compound (0.0400 g in 10 ml CD_3OD)] was added to dissolve the acid. The methyl ester (30 μl) was added from a microsyringe and, for reactions in mixed solvents, $(CD_3)_2SO$ (500 μl), C_6D_6 (500 μl), or D_2O (250 μl) was added before the liquid was made up to the mark with CD_3OD containing the reference compound. Ten micro-n.m.r. tubes were filled with this solution by using a microsyringe. The sealed tubes were placed in Polythene pockets in a thermostatically controlled oil-bath and, at intervals, a tube was removed, cooled successively in water, ice–salt, and solid carbon dioxide–acetone, and finally stored in liquid air or liquid nitrogen until required for n.m.r. analysis. The n.m.r. spectrum of each sample was recorded at least three times by using an upfield sweep with the spectrometer locked onto the residual OH absorption of the solvent and the catalyst. The region of the spectrum recorded showed the OCH_3 ester absorption, the CH_3OD absorption for the residual protons in the solvent and for the methanol produced in the reaction, the reference absorption for the CH_3 groups of 1,2,4,5-tetramethylbenzene, and the CH_3 absorption of the catalyst.

Kinetic Procedure for Base-catalysed Methanolyses of Relatively Unreactive Esters.—Sodium (*ca.* 0.002 00 g) was introduced into a pre-weighed, calibrated, graduated flask (volume *ca* 1.600 ml) in a dry-box under nitrogen; the flask and contents were reweighed. A small amount of CD_3OD, containing the reference compound, was added to react with the sodium to produce CD_3ONa. The methyl ester (30 μl) was then added and the subsequent procedure was as described above.

Kinetic Procedure for Base-catalysed Methanolyses of Relatively Reactive Esters.—Sodium methoxide solution was prepared by the reaction of sodium [*ca.* 0.002 00 g; accurately weighed into a calibrated, graduated flask (volume *ca.* 1.600 ml)] with a small amount of CD_3OD [containing 1,2,4,5-tetramethylbenzene as reference compound (0.0800 g in 10 ml CD_3OD)]. For reactions in mixed solvents, $(CD_3)_2SO$ (500 μl), C_6D_6 (500 μl), or D_2O (250 μl) was added before the liquid was made up to the mark with CD_3OD containing the reference compound. An accurately calibrated, graduated n.m.r. tube (500 μl) was filled to the mark with sodium methoxide solution in a dry-box. The temperature in the n.m.r. probe was measured by using a thermocouple and the sealed n.m.r. tube was placed in the probe for 15 min to attain the temperature of the probe. The tube was removed from the probe and the methyl ester (30 μl) was added (microsyringe) and the sample was rapidly and thoroughly mixed. The tube was replaced in the probe and the appropriate region of the spectrum of the sample was recorded as frequently as possible until the OCH_3 signal of the ester had disappeared. The time was noted at each recording of the ester absorption and the temperature in the probe was measured at the end of the reaction to check that it had remained constant.

The majority of the reactions carried out in the probe of the spectrometer were those of methyl cyclohexanecarboxylate, methyl *trans*-4-t-butylcyclohexanecarboxylate, and methyl *trans*-decalin-2β-carboxylate at temperatures between 10 and 40 °C, *i.e.* giving half-lives of less than 40 min at 30 °C.

Calculation of Rate Coefficients.—For each spectrum the ratio of the height of the OCH_3 signal (ester) to the height of the signal of the reference compound (ref.) was determined. A plot of log (ester)/(ref.) against time and a least-squares analysis of the data gave a value of the first-order rate coefficient, from which the second-order rate coefficient was obtained by dividing by the concentration of catalyst used. For base-catalysed reactions in the n.m.r. probe a correction was made for the change in volume produced by adding the ester to the solution in the calibrated n.m.r. tube.

Rate coefficients were reproducible within ±5% for reactions carried out in the thermostat bath, or ±8% for reactions in the spectrometer probe. We acknowledge that the results are not as reproducible as we had hoped. This was probably due to the small amounts of material used. For further discussion of the accuracy see Results and Discussion section.

RESULTS AND DISCUSSION

Detailed kinetic results are given in Supplementary Publication No. SUP 22794 (3 pp.).* For acidic or basic methanolysis of the esters in CD_3OD, values of Arrhenius parameters, and of rate coefficients at 60.0 °C (calculated from Arrhenius lines) are in Table 1. The

* For details of Supplementary Publications see Notice to Authors No. 7 in *J.C.S. Perkin II*, 1979, Index issue.

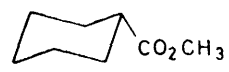
measurements span overall the range 13—130 °C, and 60 °C was chosen as a suitable comparison temperature, to minimise the amount of extrapolation for systems studied near the top or the bottom of the temperature range. The reproducibility of the results, as indicated by measures of goodness of fit to the Arrhenius line, varied considerably from one system to another, the reactions of methyl *trans*-decalin-1β-carboxylate and of methyl *cis*-4-t-butylcyclohexanecarboxylate (usually involving relatively high temperatures) being the least satisfactory.

TABLE 1

Arrhenius parameters for acidic or basic methanolysis of methyl esters in CD_3OD [E/kcal mol^{-1}, $\log_{10}(A/s^{-1})$; 10^4k(calc.), 60.0 °C/l mol^{-1} s^{-1}]

	T/°C	n [a]	E [b]	$\log_{10}A$ [b]	r [c]	s [d]	10^4k(calc.), 60.0 °C
Acidic methanolysis							
Methyl cyclohexanecarboxylates							
Parent	40—61	6	12.46 (0.45)	5.65 (0.30)	0.997	0.019	29.9
cis-4-t-Butyl *ax*	71—91	7	12.57 (0.85)	4.67 (0.53)	0.989	0.030	2.62
trans-4-t-Butyl *eq*	40—61	7	12.48 (0.26)	5.75 (0.18)	0.999	0.012	36.5
Methyl *trans*-decalincarboxylates							
-1α- *eq*	71—96	8	12.63 (0.23)	3.73 (0.14)	0.999	0.011	0.278
-1β- *ax*	112—130	6	17.36 (1.16)	5.66 (0.64)	0.991	0.030	0.0187
-2α- *ax*	50—81	6	13.68 (0.48)	5.18 (0.31)	0.998	0.028	1.60
-2β- *eq*	40—61	9	11.97 (0.45)	5.40 (0.31)	0.995	0.026	35.2
Basic methanolysis							
Methyl cyclohexanecarboxylates							
Parent	13—35	10	11.80 (0.49)	6.78 (0.37)	0.993	0.037	1087
cis-4-t-Butyl *ax*	40—56	11	14.44 (0.94)	7.27 (0.64)	0.981	0.036	63.3
trans-4-t-Butyl *eq*	15—38	10	11.05 (0.56)	6.27 (0.40)	0.990	0.034	1063
Methyl *trans*-decalincarboxylates							
-1α- *eq*	40—60	6	16.22 (0.25)	7.16 (0.20)	0.999	0.010	3.36
-1β- *ax*	70—96	10	19.94 (1.49)	8.87 (0.91)	0.978	0.076	0.620
-2α- *ax*	40—61	8	14.60 (0.42)	7.28 (0.28)	0.998	0.020	50.6
-2β- *eq*	18—41	13	12.35 (0.35)	7.19 (0.25)	0.996	0.027	1220

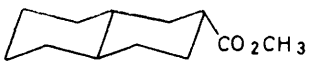
[a] Number of points. [b] Standard error in parentheses. [c] Correlation coefficient. [d] Standard deviation of estimate ($\log_{10}k$).



(I)

(II)

(III)



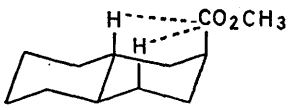
(IV)

Acidic Methanolysis in CD_3OD.—The pattern of the rate coefficients at 60 °C resembles that found previously for acid-catalysed esterification of the carboxylic acids in methanol at 30 °C.[4] The parent ester (I) gives a rate coefficient close to that for methyl *trans*-4-t-butylcyclohexanecarboxylate (II), and lying between this and that for the *cis*-compound (III) (*cf.* acid-catalysed hydrolysis).[2] The decalin-2β-yl compound (IV) and the *trans*-compound (II) (both *eq*) give values in close agreement, but the rate coefficient for the *cis*-compound (III) is *ca.* 60% higher than that for the decalin-2α-yl compound (V). While the latter is entirely *ax*, the former contains a small percentage of a twist-boat form, in which the ester group is effectively equatorial.[3] This particular '2α/*cis*' discrepancy is the largest we have observed.[3,4] The ratio 2β/2α is 22, comparable with 25.5 for acid-catalysed esterification at 30 °C.[4]

The decalin-1β-yl compound (*ax*) (VI) is easily the least reactive, as expected, since it has three 1 : 3 interactions. The decalin-1α-yl compound (*eq*) (VII) is, however, less reactive than the 2α-compound (*ax*), even though it has only one 1 : 3 interaction. This is a further example of the anomalous behaviour of the decalin-1α-yl system, to which we first drew attention *ca.* 15 years ago, and which, as far as we are aware, has not been explained.[14]

We note also that the peculiar behaviour of the decalin-1α-yl compound arises from a low value of log A, while the very low reactivity of the decalin-1β-yl compound is due to a high value of E.

Basic Methanolysis in CD_3OD.—Values of the rate coefficients at 60 °C for the parent ester and methyl *trans*-4-t-butylcyclohexanecarboxylate lie very close together. (The actual measurements, at *ca.* 15—35 °C, show the *trans*-compound to be slightly more reactive than the parent.) This is to be contrasted with the



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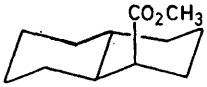
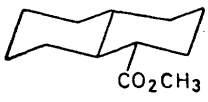


(VI)



(VII)

alkaline hydrolysis of esters in aqueous organic solvents in which the parent/*trans* ratio is solvent dependent and varies between *ca.* 0.8 and 1.3.[3] In aqueous alcoholic solvents it is always <1. Methyl *trans*-4-t-butylcyclohexanecarboxylate and the decalin-2β-yl ester differ in rate coefficient at 60 °C by *ca.* 15%. However, in the experimental temperature range (15—40 °C) the correspondence is much closer. The difference between the results extrapolated to 60 °C is due to a difference in the observed activation energies.

The reaction of methyl *cis*-4-t-butylcyclohexanecarboxylate has a rate coefficient *ca.* 25% higher than that for the decalin-2α-yl compound. This is comparable with what was observed for alkaline ester hydrolysis [3] (for an explanation, see above). As with the acid-catalysed reaction, the least reactive compound is the decalin-1β-yl ester, with the decalin-1α-yl system presenting yet another example of its anomalous behaviour.

Methyl *trans*-decalin-1β-carboxylate gives easily the highest value of E, and an enhanced log A. The difference in reactivity of the decalin-2α- and -2β-yl compounds is attributable to a difference in E, the log A values being similar. There are some parallels between the E values for the present reaction and those of alkaline ester hydrolysis.[3]

Methanolysis in Mixed Solvents.—Table 2, in the same form as Table 1, summarises the kinetic results for acidic or basic methanolysis of methyl *trans*-decalin-2-carboxylates in CD_3OD–$(CD_3)_2SO$ (solvent B), CD_3OD–C_6D_6 (solvent C), CD_3OD–D_2O (solvent D), and, for comparison, CD_3OD (solvent A as in Table 1), the mole fraction of CD_3OD in A—D, being respectively 1.00, 0.80, 0.83, and 0.71.

Acidic Methanolysis.—The addition of DMSO (solvent B) considerably reduces the rate coefficient for both equatorial and axial ester groups. This may be due partly to the increase in dielectric constant from 33.7 (20 °C) to 40.6 (20 °C) [15,16] but seems likely to be due mainly to the highly basic DMSO competing for the hydrogen ions and reducing their effective catalytic power. This involves an increase in E, with log A remaining constant.

The addition of benzene (solvent C) has a relatively weak retardatory effect. The dielectric effect here should be acceleratory,[16] so any contrary influence is partially masked. There would, of course, be a small retardatory effect associated with the dilution of CD_3OD but the principal effect is probably connected with the effect of the benzene on the hydrogen-bonded structure of CD_3OD. This manifests itself in a reduced log A value and a slightly reduced E.

The retardatory effect of D_2O (solvent D) is intermediate between those of DMSO and C_6D_6. The addition of D_2O will introduce a competition for the D^+ ions, and D_3O^+ is a less effective catalyst than $CD_3OD_2^+$. However, in competition with this will be the intervention of hydrolysis as well as exchange (see above). As far as the effect on k is concerned, the former is apparently dominant.*

Basic Methanolysis.—In contrast to the above reactions addition of DMSO accelerates this reaction (solvent B). This is may be ascribed to desolvation of CD_3O^- on addition of DMSO, which will associate strongly with CD_3OD but not with CD_3O^-. The acceleration is more pronounced for the reaction of the axial ester group; desolvation thus seems more significant for a hindered reaction site.

As for the acidic reactions, benzene has a retardatory

TABLE 2

Arrhenius parameters for acidic or basic methanolysis of methyl *trans*-decalin-2-carboxylates in A,[a] CD_3OD; B,[a] CD_3OD–$(CD_3)_2SO$; C,[a] CD_3OD–C_6D_6; D,[a] CD_3OD–D_2O [E/kcal mol^{-1}; $\log_{10}(A/s^{-1})$; 10^4k(calc.), 60.0°/l mol^{-1} s^{-1}]

		Solvent	T/°C	n [b]	E [c]	$\log_{10}A$ [c]	r [d]	s [e]	10^4k(calc.), 60.0 °C
Acidic methanolysis									
-2α-	*ax*	A	50—81	6	13.68 (0.48)	5.18 (0.31)	0.998	0.028	1.60
		B	65—108	12	14.71 (0.54)	4.77 (0.33)	0.993	0.044	0.131
		C	75—97	6	11.44 (0.30)	3.49 (0.18)	0.999	0.011	0.974
		D [f]	65—96	9	15.95 (0.25)	6.11 (0.16)	0.999	0.016	0.448
-2β-	*eq*	A	40—61	9	11.97 (0.45)	5.40 (0.31)	0.995	0.026	35.2
		B	70—91	6	13.57 (0.36)	5.31 (0.22)	0.999	0.013	2.56
		C	64—95	7	11.37 (0.43)	4.69 (0.27)	0.996	0.022	17.1
		D [f]	50—80	8	14.75 (0.56)	6.49 (0.37)	0.996	0.034	6.47
Basic methanolysis									
-2α-	*ax*	A	40—61	8	14.60 (0.42)	7.28 (0.28)	0.998	0.020	50.6
		B	31—50	6	14.16 (0.37)	7.22 (0.26)	0.999	0.016	86.3
		C	50—71	6	16.17 (0.64)	8.21 (0.42)	0.997	0.026	40.2
		D [f]	40—70	8	13.80 (0.30)	6.80 (0.20)	0.999	0.019	55.6
-2-β-	*eq*	A	18—41	13	12.35 (0.35)	7.19 (0.25)	0.996	0.027	1220
		B	10—34	15	10.91 (0.39)	6.31 (0.29)	0.992	0.034	1432
		C	32—48	11	10.67 (0.80)	5.84 (0.56)	0.975	0.037	686
		D [f]	27—46	8	8.67 (0.57)	4.53 (0.41)	0.987	0.026	690

[a] Mole fraction of CD_3OD. A, 1.00; B, 0.80; C, 0.83; D, 0.71. [b] Number of points. [c] Standard error in parentheses. [d] Correlation coefficient. [e] Standard deviation of estimate ($\log_{10}k$). [f] The results are for methanolysis and hydrolysis combined; see main text.

* In the initial state, the charge is more concentrated than in the relevant activated complex and consequently the solvent effect on the initial state will be the dominant factor.

effect, although the effect for the axial group is rather feeble. Competition between effects probably occurs: desolvation and the dielectric effect in opposition to the liquid structure effect, with the latter on balance a little more important.

Solvent D presents a complicated situation. The addition of D_2O slightly accelerates the reaction of the axial ester group but it considerably retards that of the equatorial. However, there is a considerable reduction in E for the equatorial group, and at much lower temperatures there would be a reversal of the effect: the equatorial group reaction would be faster in solvent D than in A. The dielectric effect and the increase in solvation of CD_3O^- would cause a decrease in rate coefficient while the occurrence of hydrolysis in addition to exchange would tend to increase the rate.

Finally we offer a generalisation about the Arrhenius parameters in methanolysis in the four solvents: for *ax* compared with *eq* in a given solvent, in the acidic reaction *ax* always has higher E and lower log A, while in the basic reaction *ax* always has higher E and higher log A.

Methanolysis of Methyl endo- *or* exo-*Norbornane-2-carboxylate.*—The kinetic results are in Table 3 for methanolysis in CD_3OD. In the acidic reaction 10^4k for the *endo*-isomer (5.64) is several times greater than 10^4k for the 2-axial ester group in the decalin system (1.60). Apparently the three *endo*- interactions are together less important than those for the 2-*ax* [two 1 : 3, *cf.* (VIII) and (V)]. On the other hand 10^4k for the *exo*-group (24.1) is somewhat smaller than that for 2-*eq* (35.1), *cf.* (IX) and (IV). The small extra interactions indicated probably explain this. Qualitatively

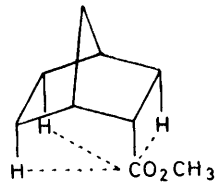
TABLE 3

Arrhenius parameters for acidic or basic methanolysis of methyl *endo*- or *exo*-norbornane-2-carboxylate in CD_3OD [E/kcal mol^{-1}; $\log_{10}(A/s^{-1})$; 10^4k(calc.), 60 °C/l mol^{-1} s^{-1}

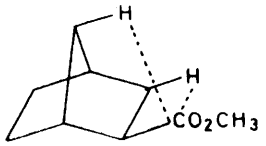
	T/°C	n [a]	E [b]	$\log_{10}A$ [b]	r [c]	s [d]	10^4k(calc.), 60.0 °C
Acidic methanolysis							
endo	70—91	6	13.25 (0.22)	5.44 (0.14)	0.999	0.008	5.64
exo	51—70	6	11.96 (0.31)	5.23 (0.20)	0.999	0.012	24.1
Basic methanolysis							
endo	31—51	6	12.57 (0.53)	6.32 (0.37)	0.997	0.022	118.5
exo	8—34	6	12.75 (0.30)	7.35 (0.23)	0.999	0.020	954

[a] Number of points. [b] Standard error in parentheses. [c] Correlation coefficient. [d] Standard deviation of estimate ($\log_{10}k$).

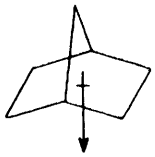
the same situation holds in the basic reaction: $k_{endo} \gg k_{2\text{-}ax}$, $k_{exo} < k_{2\text{-}eq}$. However there are considerable quantitative differences in that $k_{2\text{-}eq}/k_{2\text{-}ax}$ is 21.9 in acidic and 24.6 in basic methanolysis, (*i.e.* the ratios are similar, see later) but while k_{exo}/k_{endo} is 4.27 in acidic methanolysis, the ratio in the basic reaction is very different, 8.05. We attribute this to an appreciable polar effect of the norbornyl group in the basic methanolysis. Norbornane itself has a dipole moment of 0.58 D directed along the vertical axis of the molecule as shown in (X).[17] Acid-catalysed reactions of esters are considerably less sensitive to polar effects than base-catalysed hydrolyses and related reactions [5] (see discussion of the bicyclo-[2.2.2]octane system below), and thus the influence of the norbornane dipole will be seen in the latter rather than the former. The approach of the CD_3O^- ion to the carbonyl reaction centre will be opposed more for the *endo*-ester group than for the *exo*, and thus k_{exo}/k_{endo} will be increased in the basic reaction compared with the



(VIII)



(IX)



(X)

acidic (assuming that the steric effects are comparable; see later).

Methanolysis of Methyl Bicyclo[2.2.2]*octane-*1*-carboxylate and its* 4*-Bromo-derivative.*—Scarcity of material prevented a thorough study of these systems. However, from measurements between 70 and 90 °C, 10^4k at 60 °C for the acidic reaction was *ca.* 3.5 for the 4-H, and 2.5 for the 4-Br compound, while for the basic reaction 10^4k at 60 °C was *ca.* 88 for the 4-H (measurements between 40 and 55 °C) and *ca.* 755 for the 4-Br compound (measurements between 26 and 36°). Thus, under conditions of constant steric effect, the electron-attracting influence of 4-Br is only mildly retardatory in the acidic reaction. Qualitatively this corresponds to the small negative ρ value for acid-catalysed esterification of benzoic acid in methanol.[5] On the other hand, 4-Br strongly accelerates the basic methanolysis. This corresponds qualitatively to the substantial positive ρ value for the alkaline hydrolysis of alkyl benzoates in aqueous organic solvents.[5]

The Taft Analysis.—Of the various pairs of conformers studied in the present work, only methyl *trans*-decalin-2β- and -2α-carboxylate are suitable for examining Taft's assumption regarding the equality of steric effects as between acidic and basic ester reactions. The methyl *trans*- and *cis*-4-t-butylcyclohexanecarboxylates, whose behaviour first aroused our suspicions about Taft's assumption,[2] are in fact not entirely suitable for the purpose because the conformational locking in the *cis*-compound is not fully effective (see earlier).[3,4] It would be unwise to base any critique of the Taft analysis on the decalin-1α- and -1β-yl pair, because the behaviour of the

1α-compound (*eq*) is not understood (see earlier). The norbornane system has already been shown to exhibit a conformationally dependent polar effect in the basic reaction, and is thus incapable of revealing anything about the constancy or lack of it in steric effects as between acidic and basic reactions.

We are thus left with the decalin-2β- and -2α-yl compounds. At this stage we continue to assume that this system will not show any conformationally dependent polar effect in the basic reaction, as we have done from the outset of this work. (However, at the end we shall briefly discuss the validity of this assumption.) Thus the k_{eq}/k_{ax} ratios will be taken as measuring the difference in the steric effects in the reactions of the two conformers, and, if Taft's assumption is correct, under given conditions these ratios should be equal for the acidic and basic reactions. The ratios for the four solvent systems A—D are in Table 4 for four temperatures in the range

TABLE 4

Ratios of rate constants (k_{eq}/k_{ax}) for the reactions of methyl *trans*-decalin-2β- and -2α-carboxylates and corresponding values of (k_{eq}/k_{ax})basic/(k_{eq}/k_{ax})acidic at several temperatures

	Solvent [a]	40.0 °C	50.0 °C	60.0 °C	70.0 °C
Acidic methanolysis					
	A	26.2	23.4	21.9	20.4
	B	21.9	20.4	19.5	18.6
	C	17.3	17.8	17.8	17.7
	D	16.6	15.5	14.5	14.2
Basic methanolysis					
	A	30.2	26.9	24.6	21.9
	B	22.9	19.5	17.4	14.4
	C	29.5	22.4	17.4	13.5
	D	20.4	15.9	12.3	10.0
(k_{eq}/k_{ax})basic/(k_{eq}/k_{ax})acidic					
	A	1.15	1.15	1.12	1.07
BA ratio	B	1.05	0.96	0.89	0.77
	C	1.71	1.26	0.98	0.76
	D	1.23	1.03	0.85	0.70

[a] See Table 2.

40—70 °C. The reactions should be examined at several temperatures in order to minimise the effects of extrapolation or interpolation of results, and of varying degrees of reproducibility on the reliability of the results. We also present the values of $(k_{eq}/k_{ax})_{basic}/(k_{eq}/k_{ax})_{acidic}$ (the *BA* ratio) in Table 4. For perfect conformity to Taft's assumption, these should all be unity. We discuss the various solvent systems in order.

Solvent A. Here we are dealing only with the exchange reaction in a one-component solvent. The average *BA* ratio between 40 and 70 °C is 1.12 ± 0.04, with a slight systematic variation with temperature. Detailed inspection of our results suggests that those at 40 and 50 °C should be the most reliable, but however, these results are viewed, Taft's assumption appears to hold fairly closely for this system. A departure of 12% from unity in the *BA* ratio would lead to an error of (log 1.12)/2.48 = 0.02 in the calculation of a σ* value,[5] which might be relatively important for certain feebly polar substituents such as alkyl groups, but which would not be significant for a substituent of considerable polarity.

Solvent B. The value of k_{eq}/k_{ax} for basic methanolysis in CD_3OD–$(CH_3)_2SO$ is clearly temperature dependent and this leads in turn to temperature dependence of the *BA* ratio. The average for the four temperatures is 0.92. We regard the results at 40 and 50 °C as rather more reliable than those for 60 and 70 °C. As already seen, the effect of adding DMSO on the individual rate coefficients was very large for the acidic reaction; it was less marked for the basic reaction, but was in the opposite direction. Nevertheless the *BA* ratio is still fairly close to unity.

Solvent C. Here there is a much larger temperature effect on the *BA* ratio. This arises from a considerable temperature effect on (k_{eq}/k_{ax}) for the basic reaction, with virtual temperature independence of this ratio for the acidic reaction. (It should be noted that the results for the basic reaction in this solvent system are the least reproducible of any in this work.) This may be connected with the peculiarities of this unusual solvent system, CD_3OD–C_6D_6 for ester reactions, and perhaps these results are the least relevant to a scrutiny of the validity of Taft's assumption for more usual media for ester reactions. However, excluding the situation for 40 °C (which involves very considerable extrapolation for the acidic reactions), the *BA* ratio is still fairly close to unity on average, and is very close to unity at 60 °C, the temperature for which we consider the results to be most reliable. Excluding 40 °C, the error in σ* (estimated as above) is still not more than *ca.* 0.04.

Solvent D. As already mentioned, the rate constants measured for this system, CD_3OD–D_2O, must be presumed to be total coefficients for the two reactions of exchange and hydrolysis occurring in unknown proportions. Here again there is a pronounced temperature effect (not so large as with C), and this is connected with a difference of *ca.* 5 kcal mol^{-1} for the *E* values of the basic reactions. The results at 50 °C are probably the most reliable, and the *BA* ratio is 1.04. Thus the exchange reaction and the hydrolysis together appear to conform fairly well to Taft's assumption of the equality of steric effect as between acidic and basic ester reactions.

Conclusions.—Comparison of the rates of methoxy exchange of methyl *trans*-decalin-2α- or -2β-carboxylate in acidic and in basic conditions, in various solvent systems and at temperatures *ca.* 20 °C above room temperature (*i.e.* in the temperature region in which studies of esterification and hydrolysis are usually carried out) indicates that Taft's assumption, regarding the equality of steric effects in acidic and basic reactions, holds with reasonable precision. Certainly the inequality of steric effects shown by these experiments would not significantly affect σ* values, except possibly for the less polar alkyl groups.

Finally we must return to the question of whether the system of our choice is really adequate for testing Taft's assumption. Are the polar effects of the decalin system upon the axial or equatorial reaction centre essentially the same, so that the basic reaction, which is much more sensitive to polar effects than the acidic reaction, is, like the acidic reaction, dependent only on steric effects? If the polar effect were solely the classical through-bond

inductive effect then an affirmative answer could be given. If, however, any field component is involved, this will depend on bond angles and distances which are not all the same as between the two conformers. We were able to recognise the unsuitability of the norbornane system by pointing to the permanent dipole moment of the parent hydrocarbon, which inevitably leads to a different field effect for *endo*- and *exo*-reaction sites. *trans*-Decalin has no permanent dipole moment [18] so the system does not fail on that score. However, there is some evidence that *trans*- and *cis*-4-t-butylcyclohexyl bromides or the corresponding alcohols differ in dipole moment by *ca.* 0.1 D.[19] There does not appear to be such direct evidence about *trans*-decalin-2α- and -2β-yl derivatives but dipole moments of dichlorocholestane derivatives suggest that there may be some difference as between corresponding 2-*eq* and 2-*ax* derivatives in the decalin system.[19]

Such evidence certainly raises the possibility that 2-*eq* and 2-*ax* reaction sites will experience a slightly different field effect. Could this be serious enough to vitiate the comparison we have made? All we can say is that such an effect is probably far less serious than the one we detected in the norbornane system and while the *trans*-decalin-2-yl system may not be perfect for our purpose, it is the best system we have thought of to date for testing Taft's assumption.

We have tried to compare the electronic effects for axial and equatorial sites by CNDO/2 and INDO calculations. Such calculations require numerous assumptions about molecular geometry and yield values for electron populations on atoms. Assumptions must then be made to relate these to chemical reactivity. We concentrated on the problem of trying to discover any feature of the electron populations of cyclohexane- or *trans*-decalin-carboxylic acids which would account for an *eq*-CO_2H being *ca.* 50% more reactive than an *ax*-CO_2H towards diazodiphenylmethane, a difference which we normally ascribe to a steric effect.[14] We have been unable to find any such feature of the electron populations. Calculations on species more closely related to the actual reactants in our methoxy exchange work, or *ab initio* calculations, are beyond practicability at present.

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