The Separation of Polar and Steric Effects. Part 15.[1] Kinetics of the Reactions of Benzoic Acid and of *ortho*-Substituted Benzoic Acids with Diazodiphenylmethane in Various Aprotic Solvents

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Rate coefficients at 30 °C have been measured for the reactions of benzoic acid and a large series of *ortho*-substituted benzoic acids with diazodiphenylmethane (DDM) in 7 aprotic solvents. The dependence of the second-order rate coefficents on the initial concentration of the acid has been examined for some of the systems. For reactions in a given aprotic solvent the log *k* values for the various acids (determined as far as possible with standard [acid]) were correlated by means of the appropriate form of the extended Hammett equation with inductive, resonance, and steric parameters. The correlation equations were established with a limited set of substituents, whose characteristic parameters σ_I, σ_R, and υ (as determined by Charton) are well established and are unlikely to show effects due to hydrogen-bonding or substituent conformation. The results for other substituents were then interpreted by comparing values of log *k*(calc.) from a correlation expression with log *k*(obs.). The most striking finding from the analysis is the very great importance in aprotic solvents of effects involving hydrogen-bonding between *ortho*-substituent and reaction centre.

IN Part 14[1] we discussed the kinetics of the reactions of benzoic acid and of 32 *ortho*-substituted benzoic acids with diazodiphenylmethane (DDM) in 11 alcohols. The rate coefficients (30 °C) in a complete data matrix, were subjected to correlation analysis for (*a*) the solvent effect in the reactions of a given acid, (*b*) the influence of the *ortho*-substituent for the reactions in a given solvent. We now present and discuss rate coefficients for the reactions in a number of aprotic solvents. Because of limitations imposed by the insolubility of certain acids or inconveniently high or low reaction rates the data matrix is not complete. There is the added problem of appreciable concentration dependence of second-order rate coefficients in certain systems. Nevertheless useful correlation analysis can be carried out.

In several papers of this [2-5] and another series [6-8] we have discussed the kinetics and mechanism of the reactions between carboxylic acids and DDM in aprotic solvents. For many donor aprotic solvents, in which the extent of dimerisation of carboxylic acids is minute, the observed second-order rate coefficients, *k*(obs.), increase rectilinearly with [acid].[6] For solvents in which the carboxylic acid is considerably dimerised, this relationship is commonly curvilinear, and *k*(obs.) may either increase or (more rarely) decrease as the concentration is increased.[7] There are occasional examples of rectilinear behaviour or of *k*(obs.) being almost independent of concentration. (This independence is also to be observed in certain donor aprotic solvents.[6]) The mechanistic scheme [6-8] used to explain these results involves reversible formation of a complex between diazodiphenylmethane and the carboxylic acid,[9] which subsequently breaks down to products either spontaneously or under catalysis by a further molecule of acid. A mechanistic role of dimeric acid may also be invoked. Particular importance is attached to the rate coefficient k_0 obtained by extrapolation of *k*(obs.) to [acid] 0. In spite of the complex nature of k_0 (the product of a pre-equilibrium constant and the rate coefficient for a rate-*limiting* proton transfer, *cf.* the simple significance of the rate coefficients for the reactions in alcoholic solvents [1]), correlation analysis of log k_0 for benzoic acid in terms of solvent parameters is highly successful.[4,6,8]

DISCUSSION

For the reactions of benzoic acid and of 31 *ortho*-substituted benzoic acids, rate coefficients in acetone or in ethyl acetate at 30.0 °C were measured, as far as practicable at acid concentrations of 0.035, 0.0175, and 0.007M, the first-order procedure being used (see Experimental section) (Table 1). For the reactions in nitrobenzene and in chlorobenzene, limited studies at various concentrations were carried out, but the principal results were obtained with [acid] 0.007M, and for the more reactive acids we had to use the second-order procedure (Table 2). For the reactions in *NN*-dimethylacetamide (DMA), *NN*-dimethylformamide (DMF) and dimethyl sulphoxide (DMSO) more limited studies were made by the first-order procedure at [acid] 0.035M (Table 2). Earlier work had shown that for the reactions in solvents of this nature *k*(obs.) is almost independent of concentration.[6]

Usually the rate coefficients for the reactions of carboxylic acids with DDM are reproducible to within a few percent by different authors who work with different samples of reactants and solvents and with different spectrometers (*cf.* the rate coefficients for the reactions of benzoic acids with DDM in alcohols at 30.0 °C as recorded in Part 14 [1] and in Part 12 [4]). However, there are serious discrepancies between the rate coefficients for benzoic acid, *o*-alkylbenzoic acids, and *o*-halogenobenzoic acids in DMF measured in the present work and in a former study.[3] In the worst case, *o*-t-butylbenzoic acid, the new value is about four times the old. There is also some disagreement, but not so serious, between the new and the old values for the reactions of the above acids in DMSO. Such records as survive from the former study do not shed light on the situation. We have satisfied ourselves that the present results should be regarded as the more reliable. The patterns of the new

TABLE 1

Rate coefficients (l mol^{-1} min^{-1}) for the reactions between diazodiphenylmethane and *ortho*-substituted benzoic acids in acetone and in ethyl acetate at 30.0 °C at various acid concentrations (M)

	Acetone			Ethyl acetate		
Substituents	0.035	0.0175	0.007	0.035	0.0175	0.007
H *	0.241	0.242	0.250	0.156	0.140	0.130
Me	0.152	0.157	0.163	0.094		
Et	0.163	0.166	0.168	0.108		
Pr^i †	0.221	0.208	0.196	0.143		
Bu^t	0.323	0.310	0.292	0.251		
F	0.877	0.897	0.871	0.514	0.508	
Cl	1.79	1.78	1.78	1.17	1.07	0.996
Br	2.21	2.21	2.22	1.45	1.38	1.23
I	2.40	2.41	2.41	1.59	1.46	1.37
CF_3	3.33	3.41	3.37	2.48	2.41	2.30
OMe	0.0496			0.0223		
OEt	0.0348			0.0153		
OPh	0.418	0.412	0.401	0.250		
NH_2	0.155	0.166	0.187	0.081		
NHMe	0.222	0.231	0.225	0.114		
NHPh	1.56	1.48	1.66	0.835	0.868	0.946
NHCOMe	10.7	11.5	11.5	7.05	7.05	7.14
OH	38.2	42.0	42.7	27.7	28.9	29.0
SH	3.39	3.66	4.02	2.57	2.49	2.53
SMe	0.599	0.631	0.662	0.379		
SO_2Me	17.2	19.5	15.0	14.4	14.7	13.8
NO_2 §	15.1	15.4	16.1	13.4	13.6	13.3
CN	7.80	8.48	8.43	7.87		
OCOMe	1.02	1.01	1.01	0.584	0.758	
CO_2Me	2.30	2.32	2.25	1.77	2.07	1.66
CO_2H ¶	11.5	12.0	11.8	‖	‖	20.4
CH_2CO_2Me	0.473	0.476	0.461	0.314		
Ph	0.461	0.442	0.455	0.322		
CH_2Ph	0.347	0.340	0.350	0.214		
$(CH_2)_2Ph$	0.273	0.278	0.285	0.196		
COPh	3.19	3.36	3.34	‖	‖	2.28
2,3-$(CH)_4$	0.428	0.406	0.399	0.230		

* At 0.028M 0.235, at 0.021M 0.238, at 0.015M 0.250 l mol^{-1} min^{-1} in acetone. † At 0.028M 0.218, at 0.021M 0.217, at 0.015M 0.201 l mol^{-1} min^{-1} in acetone. § At 0.028M 15.0, at 0.021M 15.0, at 0.014M 16.0 l mol^{-1} min^{-1} in acetone. ¶ At 0.028M 11.5, at 0.021M 11.3, at 0.015M 12.1 l mol^{-1} min^{-1} in acetone. ‖ Insufficiently soluble.

results for DMF and for DMSO closely resemble each other, are similar to the pattern for DMA, and conform entirely with the patterns for the same acids in other solvents, whereas the former results (particularly for DMF), were anomalous. We therefore regard the former values for the rate coefficients of the above acids in DMF and DMSO as superseded, and withdraw the special discussion related thereto.[3]

Concentration Effects in Aprotic Solvents.—In most previous investigations the first-order procedure has been used, and the concentration of the acid has been varied upwards from the ' standard ' concentration of 0.035M.[6,10] The experimental procedures possible in the present work enabled us to use concentrations of acid lower than the standard. The relevant results are in Tables 1 and 2. There appears to be no definite pattern of concentration effect which is characteristic of a given solvent: with certain substituents k is increased by increase in the concentration, with some substituents k is decreased by increase in the concentration, while with others it remains unaffected, or a more complicated relationship is found. The limited studies for the reaction in chlorobenzene (Table 2) show an appreciable concentration effect, whereas no such effect was previously observed for the reaction of benzoic acid with DDM in this solvent.[7,10]

In former studies involving aprotic solvents great importance was attached to comparison of extrapolated values, k_0.[6,8] In the present study the necessary extrapolations are often not practicable, so values of k at 0.007M are considered as limiting values. Results for other concentrations are sometimes perforce included.

Correlation Analysis of the Influence of ortho-*Substituents on the Reactions of Benzoic Acid with Diazodiphenylmethane in Aprotic Solvents.*—In the discussion of the work in alcohols in Part 14,[1] correlation analysis of log k values for a given substrate was possible in terms of solvent parameters. The number of solvents studied in the present Part is quite inadequate for such an analysis to be valuable. Hence correlation analysis will be for the reactions of various *ortho*-substituted acids in a given solvent, by means of multiple regression of log k on the σ_I, σ_R, and ν values of the substituents, which are tabulated in Part 14.[1]

The multiple regressions are done first with the basic set A of substituents,[1] *i.e.* H, Me, Bu^t, F, Cl, Br, I, CF_3, and CN, although the last mentioned was not available for nitrobenzene and chlorobenzene. Statistical details are in Supplementary Publication No SUP 22978 (11 pp.),* but we give some examples of the regression expressions below. Nitrobenzene, Set A (without CN)

$$\log k = 0.528 + 2.437\sigma_I + 1.285\sigma_R + 0.467\nu \quad (1)$$
$$(\pm 0.264) \quad (\pm 0.366) \quad (\pm 0.157)$$
$$n = 8, R = 0.980, s = 0.155$$

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* For details of Supplementary Publications see Notice to Authors No. 7 in *J. Chem. Soc., Perkin Trans.* 2, 1979, Index issue.

(n = no. of data points; R = multiple correlation coefficient; s = standard deviation of the estimate)

DMA, Set A

$$\log k = -1.724 + 1.995\sigma_I + 1.094\sigma_R + 0.233\nu \quad (2)$$
$$(\pm 0.132) \quad (\pm 0.175) \quad (\pm 0.089)$$
$$n = 9,\ R = 0.990,\ s = 0.091$$

Acetone, Set A

$$\log k = -0.636 + 2.272\sigma_I + 1.316_R + 0.267\nu \quad (3)$$
$$(\pm 0.152) \quad (\pm 0.202) \quad (\pm 0.103)$$
$$n = 9,\ R = 0.990,\ s = 0.105$$

The success of these correlations is comparable with that of the corresponding regressions for the reactions in alcohols.[1]

As for the alcohols,[1] further substituents are now introduced into the regressions. However, only for acetone is the full Set B available, *i.e.* Set A + Et, Pr^i, OMe, OEt, OPh, SMe, SO$_2$Me, CH$_2$Ph, and (CH$_2$)$_2$Ph. Otherwise between 12 and 17 substituents of Set B are available. Sometimes the expanded regressions have lower correlation coefficients and higher standard deviations than those involving Set A, *e.g.* equation (4)

Acetone, Set B

$$\log k = -0.587 + 2.259\sigma_I + 2.042\sigma_R + 0.287\nu \quad (4)$$
$$(\pm 0.228) \quad (\pm 0.253) \quad (\pm 0.186)$$
$$n = 18,\ R = 0.962,\ s = 0.215$$

This change is readily traced to the inclusion of OMe and OEt (see below). We give now some examples of the expanded regressions which exclude these two substituents. On balance, correlation analysis involving

Acetone, Set B (without OMe, OEt)

$$\log k = -0.626 + 2.263\sigma_I + 1.415\sigma_R + 0.264\nu \quad (5)$$
$$(\pm 0.103) \quad (\pm 0.142) \quad (\pm 0.084)$$
$$n = 16,\ R = 0.990,\ s = 0.097$$

Nitrobenzene, Set B (without CN, OMe, OEt)

$$\log k = +0.558 + 2.509\sigma_I + 1.772\sigma_R + 0.406\nu \quad (6)$$
$$(\pm 0.223) \quad (\pm 0.318) \quad (\pm 0.179)$$
$$n = 15,\ R = 0.969,\ s = 0.191$$

DMA, Set B [without OPh, OMe, OEt, CH$_2$Ph, (CH$_2$)$_2$Ph]

$$\log k = -1.726 + 1.989\sigma_I + 1.009\sigma_R + 0.202\nu \quad (6)$$
$$(\pm 0.089) \quad (\pm 0.128) \quad (\pm 0.067)$$
$$n = 13,\ R = 0.993,\ s = 0.077$$

Set B (diminished) is satisfactory for the aprotic solvents but not so successful as the corresponding regressions for the hydroxylic solvents.[1] Our remaining discussion will be on the basis of the Set B (diminished) correlations (see deposited material).

In all the correlations the σ_I term is taken in first, then the σ_R term, and finally the ν term. The coefficient of σ_I

TABLE 2

Rate coefficients (l mol^{-1} min^{-1}) for the reactions betweeen diazodiphenylmethane and *ortho*-substituted benzoic acids in aprotic solvents at 30.0 °C

Substituent	Nitrobenzene (0.007M)	Chlorobenzene (0.007M)	DMA (0.035M)	DMF (0.035M)	DMSO (0.035M)
H	4.46 †	2.19 §	0.0201	0.0464	0.0416
Me	2.19	0.990 ¶	0.0139	0.0313	0.0298
Et	2.64	1.17	0.0148	0.0343	0.0321
Pr^i	3.67	1.97 ‖	0.0188	0.0426	0.0384
Bu^t	8.47	8.93	0.0249	0.0563	0.0479
F	18.8	14.0 **	0.0653	0.146	0.137
Cl	44.7	32.9	0.122	0.271	0.248
Br	53.9	43.4	0.141	0.323	0.284
I	56.2	47.9	0.135	0.310	0.251
CF$_3$	92.1	144 [a]	0.192	0.448	0.351
OMe	0.109 ‡	0.070 ‡	0.0083		
OEt	0.0625 ‡	0.0303 ‡			
OPh	3.24	2.14			
NH$_2$	2.85	1.40 ††			
NHMe	2.84	0.963			
NHPh	20.1	9.02	0.129	0.268	0.194
NHCOMe			0.569	1.26	0.746
OH	1 052 [a]	1 352 [a]	2.13	4.02	2.47
SH	59.2	37.0	0.217	0.443	0.814
SMe	10.8	5.08	0.0487		
SO$_2$Me	464 [a]	1 120 [a]	0.562	1.24	0.805
NO$_2$	603 [a]	1 332 [a]	0.636	1.53	1.05
CN	*b*	*b*	0.460	0.998	0.651
CONH$_2$	*b*	*b*			
OCOMe	22.6	16.5	0.067		0.133
CO$_2$Me	46.7	39.7	0.108	0.256	0.216
CO$_2$H	*b*	*b*	0.082	0.206	0.167
CH$_2$CO$_2$Me	9.09	5.62			
Ph	11.4	6.19			
CH$_2$Ph	5.65	3.02			
(CH$_2$)$_2$Ph	3.84	3.32			
COPh	73.6	81.4	0.179	0.408	0.310
2,3-(CH)$_4$	6.01	3.37 §§			

† At 0.0175M 4.76, at 0.035M 4.58, at 0.0035M 4.41 [a] l mol^{-1} min^{-1}. ‡ At 0.035M. § At 0.035M 1.92, at 0.0175M 2.00 l mol^{-1} min^{-1}. ¶ At 0.035M 0.846, at 0.0175M 0.912 l mol^{-1} min^{-1}. ‖ At 0.035M 1.89, at 0.0175M 1.91 l mol^{-1} min^{-1}. ** At 0.0175M 14.2, at 0.035M 13.6 l mol^{-1} min^{-1}. †† At 0.035M 0.986, at 0.0175M 1.13 l mol^{-1} min^{-1}. §§ At 0.035M 2.24, at 0.0175M 3.10 l mol^{-1} min^{-1}.

[a] Second-order procedure. [b] Insoluble.

varies from 1.85 to 3.07, and of σ_R from 0.83 to 2.27, both ranges being rather higher than the corresponding values for the alcohols. This situation corresponds to the greater sensitivity to the polar effects of *meta*- and *para*-substituents seen in the generally higher Hammett ρ values for the reactions in aprotic solvents.[2,6] The regression coefficient of the ν term varies from 0.17 to 0.705. The secondary steric effect thus appears to show a greater sensitivity to the nature of the solvent than for the alcohols,[1] but overall the steric term makes up a smaller proportion of the total substituent effect.

Usually the parent system conforms better to the regressions for the aprotic solvents than it does for the alcohols.[1] In several of the solvents log *k*(obs.) tends to be lower than log *k*(calc.) for *o*-CF_3, as for the reactions in alcohols, and the tendency of the regressions to compress the reactivities of the *o*-alkyl- and *o*-halogeno-systems is also noticeable in certain aprotic solvents.

Interpretation of log k *Values for Substituents not included in the Regressions.*—For substituents not included in the regressions there are two main sources of deviation: [1] (*a*) resonance and steric effects may show significant conformational dependence, (*b*) favourable or unfavourable hydrogen-bonding to the reaction centre may be possible.[1]

o-OMe, *o*-OEt. As already mentioned, we had to exclude these substituents from Set B for the aprotic solvents. Large differences between log *k*(obs.) and log *k*(calc.) indicate a large unfavourable hydrogen-bonding effect, *e.g.* for *o*-OMe in chlorobenzene, log *k*(obs.) is —1.16, compared with log *k*(calc.) 0.01. Various spectroscopic studies indicate internal hydrogen bonding in these compounds.[11] The unfavourable hydrogen-bonding effect appears to be greater for OEt than OMe, which agrees with some of the physical properties of *o*-ethoxybenzoic acid, *e.g.* its extremely low m.p. of 20.7 °C.[12,*]

o-OH. The favourable hydrogen-bonding effect is very large particularly in chlorobenzene, for which log *k*(obs.) is 3.13 and log *k*(calc.) is —0.27. Clearly internal hydrogen-bonding is much increased when no external hydrogen-bonding can be provided.

o-NO_2. As for the reaction in alcohols, log *k*(obs.) lies well between the two extreme log *k*(calc.) values for coplanar and orthogonal conformations. There is thus no clear evidence of the intervention of unfavourable hydrogen-bonding here (*cf.* OMe), although some internal hydrogen-bonding has been reported from i.r. studies.[13]

o-Ph. This group appears to adopt essentially the orthogonal conformation. There is a slight tendency for log *k*(obs.) actually to lie below the log *k*(calc.) value for the orthogonal conformation, suggesting the possibility of unfavourable hydrogen-bonding involving the π-electrons of the Ph substituent, *cf.* behaviour in alcohols.

o-NH_2, -NHMe, -NHPh, -NHCOMe. With all these substituents very clear evidence of favourable hydrogen-bonding is apparent, the most pronounced effect being shown with NHCOMe. For the reactions in alcohols there was little indication of this effect for these substituents, apart from NHCOMe.

o-SH. The favourable hydrogen-bonding effect is very pronounced, *cf.* behaviour in alcohols. There is i.r. evidence for such hydrogen-bonding.[14] It seems to depend less on the nature of the aprotic solvent than for *o*-OH.

o-CO_2H, -CO_2Me. In DMA, DMF, and DMSO log *k*(obs.) agrees well with log *k*(calc.) for the orthogonal conformation, and for CO_2Me in the other aprotic solvents the conformation appears to be fairly close to orthogonal. However CO_2H in acetone and in ethyl acetate shows favourable hydrogen-bonding, which was not observed for the reactions in alcohols.[1]

o-OCOMe, -CH_2CO_2Me. These substituents conform to the regressions for aprotic solvents better than they do to the regressions for alcohols.[1] This behaviour is anomalous because the unfavourable hydrogen-bonding effect, which appears to be indicated for alcohols,[1] would be expected to be enhanced in aprotic solvents.

o-COPh. In DMA, DMF, and DMSO this substituent appears to adopt a coplanar conformation, but in the other aprotic solvents an intermediate conformation appears to be shown. There is no evidence for unfavourable hydrogen-bonding.

2,3-$(CH)_4$. Only a qualitative discussion is possible.[1] As with the results for the reactions in alcohols in the previous Part,[1] the major structural influence is the secondary steric effect of the *peri*-hydrogen atom, which is comparable with that of Pr^i, although in acetone the accelerating influence exceeds that of Bu^t.

EXPERIMENTAL

The preparation and purification of the acids,[1] of diazodiphenylmethane,[1] and the purification of the solvents [2,4] have been described previously. Our usual strict criteria of purity were always applied.[1] The principal rate measurements have also been described.[1] There is also the second-order procedure for aprotic solvents, in which the initial concentrations of acid and DDM were made exactly equal at *ca.* 0.0035M. This involved preliminary determination of the % purity of the DDM, and of the extinction coefficient of the DDM at 525 nm in the given solvent (Part 12 [4]).

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[*] While results for *o*-OPh were included in the Set B (diminished) regressions when available, the values of log *k*(obs.) were always significantly below the log *k*(calc.) values. The unfavourable hydrogen-bonding effect thus operates with this substituent, but to a smaller extend than with OMe or OEt. This is probably due to the electron-attracting nature of Ph in OPh.

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