Nucleophilic Substitution Reactions of Aliphatic and Aromatic Carboxylate Ions with Ethyl Iodide. Specific Interactions and Isokinetic Relationships in Acetonitrile–Methanol Mixtures

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Transfer enthalpies for the transition-state anions in the reactions of the carboxylate anions adamantane-1-carboxylate, pivalate, benzoate, and 4-nitrobenzoate with ethyl iodide have been determined in acetonitrile–methanol mixtures (AN–MeOH). After the separation of these enthalpies into their constituent terms, *i.e.*, physical interaction and specific interaction enthalpies, the number of methanol molecules hydrogen-bonded to the anion has been evaluated on the basis of the assumption that the isokinetic relationship is realized between activation parameters, which can be identified as physical interaction quantities. An empirical correlation was observed between that number and the specific interaction enthalpy, $\Delta H_{t,Sl}^{AN \rightarrow MeOH}$, for the anion. On the basis of the AM1 model calculations, discussion is given on the factors which affect the physical interaction enthalpy.

Traditionally, studies on nucleophilic substitution reactions have been carried out in aqueous–organic solvents.[1,2] Since the pioneering work by Parker *et al.*, the special role that protic solvents play in solvating anions has become more widely appreciated. This, in turn, has led to a considerable amount of work on nucleophilic substitution reactions in terms of free-energy measurements in dipolar aprotic solvents.[3,4] Comparative studies on anion solvation in protic solvents with those in dipolar aprotic solvents would be highly desirable for the development of reaction theory in solution, as well as for quantitative documentation of the special features of protic solvent–anion interactions.

Generally speaking, enthalpy and/or entropy, *i.e.* the first derivative of free energy with respect to temperature, gives much sharper responses to the perturbations introduced into the relevant system than free energy itself.[5,6] Some of the particular features on protic solvent–anion interaction, which are not well manifested in free energy changes as a result of compensation between enthalpy and entropy, might well be detected through systematic analysis on enthalpy and on entropy.

Aliphatic carboxylic acids and benzoic acids are among the most typical weak acids, and the characterization of reactivities and solvation of the conjugate-base anions of these acids is of primary importance especially in physical organic chemistry. In the first part of this series,[7] thermodynamic characterization of anion solvation has been partly completed, and in this paper much attention will be directed to the reaction behaviour of these anions with ethyl iodide. The AM1 molecular orbital calculations will be performed to test the relevance of the chemical notions derived empirically through thermodynamic and kinetic procedures to the results obtained from model molecular orbital calculations.[8]

Results

Rate constants and activation parameters for the reactions of the conjugate-base anions of certain weak acids, *i.e.* adamantane-1-carboxylate, pivalate, benzoate, and 4-nitrobenzoate ions, with ethyl iodide in acetonitrile–methanol mixtures are summarized in Table 1. Activation enthalpy *versus* activation entropy plots [(○) in Figures 1 and 2] provide a means of visualizing the characteristic difference in the reaction behaviour between aliphatic carboxylate ion and aromatic carboxylate ion as the nucleophile.

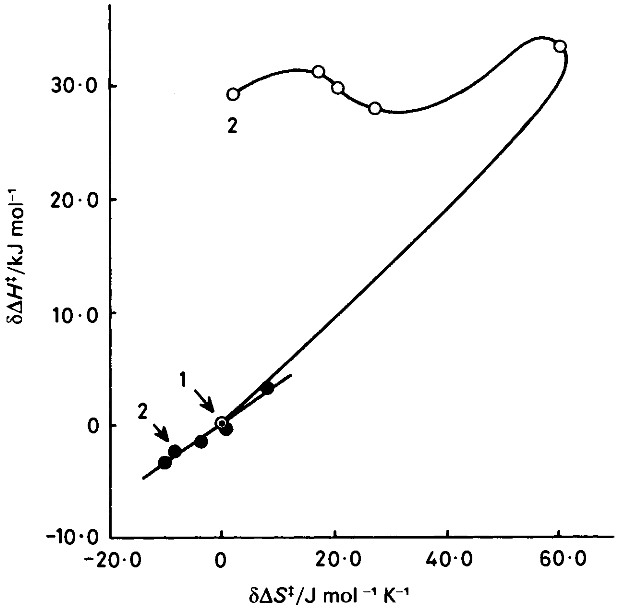


Figure 1. Activation enthalpy *versus* activation entropy correlations for the pivalate ion plus ethyl iodide reaction in acetonitrile–methanol mixtures: ○, overall quantity; ●, physical interaction quantity; 1, AN; 2, MeOH.

On the basis of a thermodynamic cycle, transfer enthalpies for the activated complexes have been calculated, combining the activation enthalpies (Table 1) with the transfer enthalpies for the relevant anions[7] and for ethyl iodide,[9] and these are summarized in Table 2. For all the transition-state anions, transfer enthalpies show a minimum at a small composition of methanol. However, a definite increase in transfer enthalpies at higher methanol compositions for the transition-state anions where the aromatic carboxylate ion has acted as a nucleophile,

Table 1. Rate constants and activation parameters in acetonitrile–methanol mixtures (30.0 °C).

	Adamantane-1-carboxylate + EtI			Pivalate + EtI		
x_{MeOH}^a	k/ 10^{-6} dm^3 mol^{-1} s^{-1}	$\Delta H^{\neq}$/ kJ mol^{-1}	$\Delta S^{\neq}$/ J K^{-1} mol^{-1}	k/ 10^{-6} dm^3 mol^{-1} s^{-1}	$\Delta H^{\neq}$/ kJ mol^{-1}	$\Delta S^{\neq}$/ J K^{-1} mol^{-1}
0	3.80×10^5	56.5 ± 0.5	−66.7 ± 1.8	2.86×10^5	63.2 ± 1.1	−47.0 ± 3.6
0.10	825.00	89.1 ± 0.6	−10.2 ± 1.9	680.00	96.6 ± 2.1	13.0 ± 6.9
0.25	121.00	96.2 ± 1.2	−2.7 ± 3.9	112.50	91.1 ± 0.9	−20.1 ± 2.7
0.50	29.40	93.1 ± 0.5	−24.7 ± 1.7	24.80	93.0 ± 1.0	−26.4 ± 3.3
0.75	10.70	96.4 ± 0.3	−22.2 ± 0.9	9.04	94.4 ± 1.0	−30.2 ± 3.3
1.0	4.26	93.4 ± 2.6	−39.8 ± 8.2	3.48	92.3 ± 1.0	−45.1 ± 3.1
Benzoate + EtI				4-Nitrobenzoate + EtI		
0	4.78×10^4	61.9 ± 0.4	−66.0 ± 1.3	1.07×10^4	68.0 ± 0.3	−58.3 ± 1.0
0.10	286.50	89.1 ± 0.4	−19.1 ± 1.2	150.00	87.8 ± 0.4	−28.3 ± 1.2
0.25	47.70	92.5 ± 0.5	−22.45 ± 1.7	28.90	92.0 ± 0.5	−28.5 ± 1.8
0.50	13.80	95.9 ± 1.0	−22.0 ± 3.3	8.34	94.8 ± 0.3	−29.5 ± 1.1
0.75	4.77	96.8 ± 1.7	−27.9 ± 5.4	2.57	99.1 ± 1.1	−24.9 ± 3.6
1.0	1.58	104.5 ± 1.5	−11.3 ± 4.8	0.920	111.3 ± 0.9	6.61 ± 3.0

[a] x_{MeOH} is the mole fraction of methanol.

Table 2. Enthalpies (kJ mol^{-1}) of transfer for transition-state anions and interaction parameters in acetonitrile–methanol mixtures (25.0 °C).

	x_{MeOH}								
Mixture	0	0.10	0.25	0.50	0.75	1.0	$\Delta H_{t,Phys}^{AN\rightarrow MeOH}$/ kJ mol^{-1}	$\Delta H_{t,SI}^{AN\rightarrow MeOH}$/ kJ mol^{-1}	K_{SE}
Adamantane-1-carboxylate + EtI	0	−6.0	−5.5	−9.8	−6.05	−7.3	3.7	−11.0	8.0
Pivalate + EtI	0	−4.3	−13.1	−10.2	−6.5	−6.5	5.5	−12.0	20.0
Benzoate + EtI	0	−3.0	−2.1	1.7	5.1	15.1	24.1	−9.0	11.0
4-Nitrobenzoate + EtI	0	−4.0	−2.0	2.9	10.25	25.0	35.0	−10.0	18.0

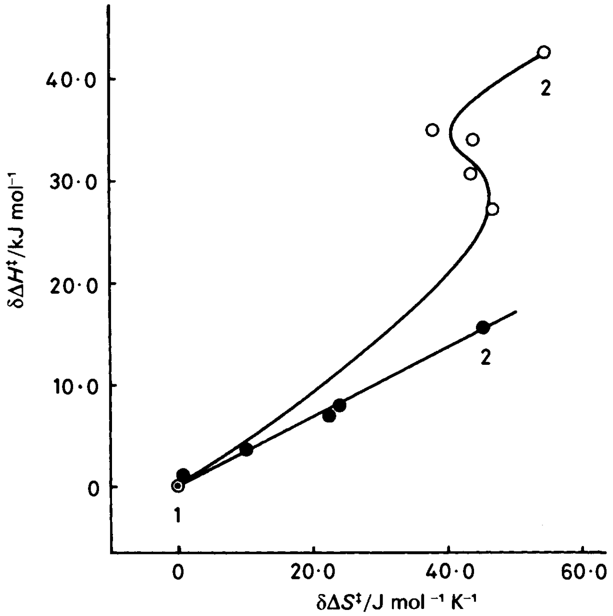


Figure 2. Activation enthalpy *versus* activation entropy correlations for the benzoate ion plus ethyl iodide reaction in acetonitrile–methanol mixtures: ○, overall quantity; ●, physical interaction quantity; 1, AN; 2, MeOH.

is quite in contrast with the less well-defined pattern, *i.e.*, a much smaller increase, in the transfer enthalpy profiles for those transition states derived from aliphatic carboxylate ion as the nucleophile.

Thus, on empirical grounds, contrasting behaviour in the reactions of aliphatic carboxylate ion as the nucleophile with those in aromatic carboxylate ion reactions could be detected through these two procedures, *i.e.* $\delta\Delta H^{\ddagger}$ *vs.* $\delta\Delta S^{\ddagger}$ plots and transfer enthalpy *versus* solvent composition profiles.

Discussion

For a comprehensive discussion on nucleophiles solvation as well as on transition-state anion solvation, a systematic analysis on the same theoretical basis will be used, if the quasi-thermodynamic assumption at the transition state is pertinent.

Transfer enthalpies of the transition-state anions were analysed on the basis of equations (1) and (2), of which the

$$\Delta H_t^{AN\rightarrow mix} = \Delta H_{t,PHYS}^{AN\rightarrow MeOH} \times x_{MeOH} \times \{1 - [1.23(x_{MeOH})(1 - x_{MeOH})]\} + \Delta H_{t,SI}^{AN\rightarrow MeOH} \times K_{SE}x_{MeOH}/(x_{AN} + K_{SE}x_{MeOH}) \quad (1)$$

$$\Delta H_t^{AN\rightarrow MeOH} = \Delta H_{t,PHYS}^{AN\rightarrow MeOH} + \Delta H_{t,SI}^{AN\rightarrow MeOH} \quad (2)$$

physical significance has been discussed elsewhere,[7] and the parameters derived are also given in Table 2. The reproducibility was quite good for the transition-state anions from aromatic carboxylate ion as the nucleophile *i.e.*, the maximum deviation is ±2 kJ mol^{-1}, and reasonable for those from aliphatic carboxylate ion as the nucleophile, *i.e.*, the maximum deviation is ±4 kJ mol^{-1}.

Table 3. Specific interaction parameters for nucleophiles and isokinetic temperatures, β_{Phys}.

	Nucleophile				
Reaction	$\Delta H_{t,\mathrm{SI}}^{\mathrm{AN}\rightarrow\mathrm{MeOH}}$/[a] kJ mol^{-1}	K_{SE}[a]	$Z(\mathrm{Nu}^-)$	$Z(\mathrm{TS}^-)$	β_{PHYS}/K
Adamantane-1-carboxylate + C_2H_5I	−49.5	41	3.7	1.0	(360)
Pivalate + C_2H_5I	−43.5	70	3.4	1.0	360
Benzoate + C_2H_5I	−36.0	58	3.0	1.0	340
4-Nitrobenzoate + C_2H_5I	−28.0	58	2.7	1.0	358

[a] Ref. 7.

There is almost the same magnitude of specific interaction at the transition state throughout the four reactions, *i.e.*, *ca.* −10 kJ mol^{-1}. This indicates that at least one molecule of methanol is hydrogen-bonded to the activated complex in the reaction, and, that the transition-state anions almost lose their individualities in terms of specific interaction enthalpy, although the actual numerical value of the term, $\Delta H_{t,\mathrm{SI}}^{\mathrm{AN}\rightarrow\mathrm{MeOH}}$ covers the range, − 49.5 for adamantane-1-carboxylate to −28.0 for 4-nitrobenzoate (in kJ mol^{-1}).[7] In contrast, the much more endothermic trend in physical interaction enthalpy, $\Delta H_{t,\mathrm{PHYS}}^{\mathrm{AN}\rightarrow\mathrm{MeOH}}$, for the transition-state anion from aromatic carboxylate ions as the nucleophile has, though less marked, its counterpart in the physical interaction enthalpy for the nucleophile, *i.e.*, $\Delta H_{t,\mathrm{PHYS}}^{\mathrm{AN}\rightarrow\mathrm{MeOH}}$ is 6.9, 9.5, 10.1, and 11.3 kJ mol^{-1} for adamantane-1-carboxylate, pivalate, benzoate, and 4-nitrobenzoate, respectively.[7]

The free energy and entropy of transfer due to a specific interaction are given by equations (3) and (4).[10] The specific

$$\Delta G_{t,\mathrm{SI}}^{\mathrm{AN}\rightarrow\mathrm{mix}} = -RT\ln(x_{\mathrm{AN}} + K_{\mathrm{SE}} \times x_{\mathrm{MeOH}})^{Z} \qquad (3)$$

$$\Delta S_{t,\mathrm{SI}}^{\mathrm{AN}\rightarrow\mathrm{mix}} = \left(\frac{Z\Delta H_{\mathrm{SE}}}{\mathrm{T}}\right)\left(\frac{K_{\mathrm{SE}}x_{\mathrm{MeOH}}}{x_{\mathrm{AN}} + K_{\mathrm{SE}}x_{\mathrm{MeOH}}}\right) + R\ln(x_{\mathrm{AN}} + K_{\mathrm{SE}}x_{\mathrm{MeOH}})^{Z} \qquad (4)$$

interaction enthalpy, $\Delta H_{t,\mathrm{SI}}^{\mathrm{AN}\rightarrow\mathrm{MeOH}}$ derived above is related to the enthalpy of the solvent-exchange process on a solvation site around the anion, ΔH_{SE}, by equation (5).[10] If the transfer

$$\Delta H_{t,\mathrm{SI}}^{\mathrm{AN}\rightarrow\mathrm{MeOH}} = Z\Delta H_{\mathrm{SE}} \qquad (5)$$

enthalpy, $\Delta H_{t,\mathrm{SI}}^{\mathrm{AN}\rightarrow\mathrm{MeOH}}$ can be separated into the constituent parameters, Z and ΔH_{SE}, by any other means, the free energy and entropy of transfer due to a specific interaction can be evaluated through equations (3) and (4) for transition-state anions and for nucleophiles. The equilibrium constants, K_{SE}, for transition-state anions have already been determined (above), and those for nucleophiles have been obtained in the first part of this series (Tables 2 and 3).

Through our work on Menschutkin reactions in acetonitrile–methanol mixtures, more informative and credible coefficients as a transition state probe could be derived, either from extended Brønsted treatments or from activation enthalpy *versus* activation entropy correlations, when physical interaction quantities instead of overall quantities were used in these correlations.[10,11]

For physical-interaction quantities to be evaluated through equations (6) and (7) [by substitution of the relevant values

$$\delta\Delta G^{\ddagger}{}_{\mathrm{PHYS}} = \delta\Delta G^{\ddagger}{}_{\mathrm{obs}} - [\Delta G_{t,\mathrm{SI}}^{\mathrm{AN}\rightarrow\mathrm{mix}}(\mathrm{TS}^-) - \Delta G_{t,\mathrm{SI}}^{\mathrm{AN}\rightarrow\mathrm{mix}}(\mathrm{Nu}^-)] \qquad (6)$$

$$\delta\Delta S^{\ddagger}{}_{\mathrm{PHYS}} = \delta\Delta S^{\ddagger}{}_{\mathrm{obs}} - [\Delta S_{t,\mathrm{SI}}^{\mathrm{AN}\rightarrow\mathrm{mix}}(\mathrm{TS}^-) - \Delta S_{t,\mathrm{SI}}^{\mathrm{AN}\rightarrow\mathrm{mix}}(\mathrm{Nu}^-)] \qquad (7)$$

calculated through equations (3) and (4) into these equations] two solvation numbers, *i.e.*, solvation numbers for nucleophile and for transition-state anion, must be determined beforehand.

The rather weak specific interaction observed for the transition-state anions, *i.e.*, $\Delta H_{t,\mathrm{SI}}^{\mathrm{AN}\rightarrow\mathrm{MeOH}}$ *ca.* −10.5 kJ mol^{-1}, corresponds to that for pyridine derivatives, *i.e.*, $\Delta H_{t,\mathrm{SI}}^{\mathrm{AN}\rightarrow\mathrm{MeOH}}$ is −9.45 and −9.0 kJ mol^{-1} for pyridine and for 4-(t-butyl)pyridine, for which the solvation number of unity was a reasonable estimate.[11] In the original deviation, the solvation number, Z in equation (5) has been introduced to represent the presence of multiple solvent exchange equilibria for a relevant solute, and thus should be an integer.[12] However, observed thermodynamic quantities are averaged values over various equilibrium processes and, as a result, the solvation number Z which gives a better simulation for the experimental results might not necessarily be an integer. In this work, experiments were carried out to determine whether reasonable isokinetic relationships exist between physical-interaction quantities, *i.e.*, between $\delta\Delta H^{\ddagger}{}_{\mathrm{Phys}}$ and $\delta\Delta G^{\ddagger}{}_{\mathrm{Phys}}$, and between $\delta\Delta H^{\ddagger}{}_{\mathrm{Phys}}$ and $\delta\Delta S^{\ddagger}{}_{\mathrm{Phys}}$, by adjusting the solvation number, Z (Nu^-) (with the solvation number for transition state anion being fixed at unity). Typical results are shown in Figures 1 and 2 [(●) in the Figures]. Solvation numbers and isokinetic temperatures, β_{PHYS} which are the average values derived through the two types of correlations, $\delta\Delta H^{\ddagger}{}_{\mathrm{Phys}}$ *vs.* $\delta\Delta G^{\ddagger}{}_{\mathrm{Phys}}$ and $\delta\Delta H^{\ddagger}{}_{\mathrm{Phys}}$ *vs.* $\delta\Delta S^{\ddagger}{}_{\mathrm{Phys}}$, are summarized in Table 3.

For the reactions of aliphatic carboxylate ion as nucleophile, those types of interactions which can experimentally be detected as physical interaction enthalpy do not indicate any significant variation on going from initial to transition state, and, as a result, the activation parameters are distributed over a narrow range around the origin [(●) in Figure 1]. In contrast, for the reactions in which aromatic carboxylate ion act as nucleophiles, the significant variation in these types of interaction can be demonstrated by the concordant variation in these activation parameters, *i.e.*, by the realization of the isokinetic relationship over a wider range [(●) in Figure 2].

Bordwell *et al.* observed an analogous phenomenon for the nucleophilic substitution in dimethyl sulphoxide (DMSO) solution in the sense that the coefficient of extended Brønsted correlation is larger for the reaction with the aromatic carbanion as nucleophile than that for the reaction with the aliphatic carbanion as nucleophile.[13]

For aromatic carboxylate ion reactions, electronic reorganization on activation would be accelerated through π-conjugative interaction between CO_2 and phenyl groups, and would be transmitted over a large number of solvent molecules around the anion. For aliphatic carboxylate ion reactions, the low polarizability of the aliphatic hydrocarbon moiety is unfavourable for electronic reorganization and since the steric bulk hinders the approach of solvent molecules to the anionic centre, the inhibition of transmission of electronic redistribution results.

Solvation numbers for nucleophiles have been determined under the assumption that the isokinetic relationship is realized

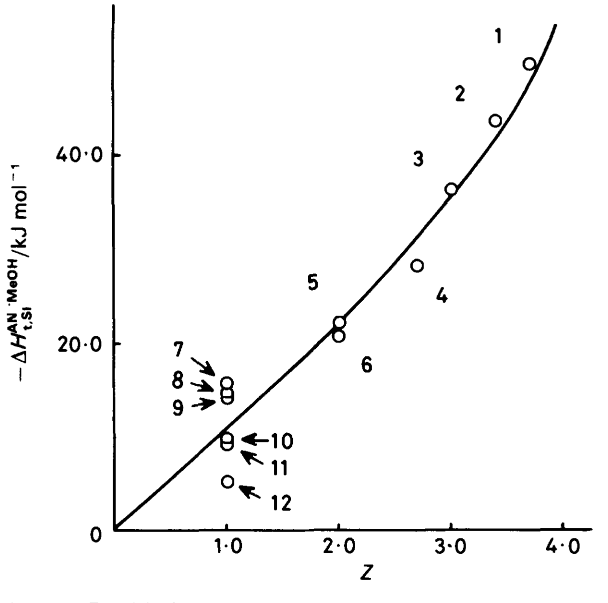
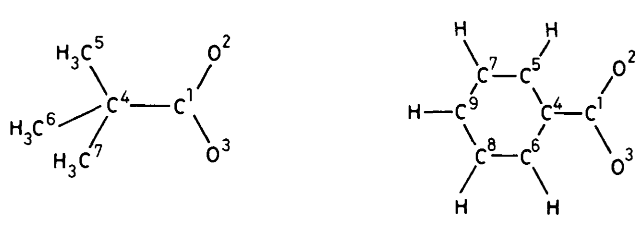


Figure 3. Empirical correlation between the negative sign of specific interaction enthalpy ($-\Delta H_{t,SI}^{AN\rightarrow MeOH}$) and solvation number, *Z*. 1, adamantane-1-carboxylate ion; 2, pivalate ion; 3, benzoate ion; 4, 4-nitrobenzoate ion; 5, quinuclidine; 6, triethylamine; 7, 4-dimethylaminopyridine; 8, *N*-methylimidazole; 9, *N*-methylbenzimidazole; 10, pyridine; 11, 4(t-butyl)pyridine; 12, 4-cyanopyridine. Experimental results which have not been summarized in Table 3, are taken from refs. 10, 11, and 14.

Table 4. AM1 atomic and group charges for nucleophiles.

Pivalate		Benzoate	
Group	Charge	Group	Charge
CH_3 (7)[a]	−0.0152	CH (9)	−0.0642
CH_3 (6)	−0.0155	CH (7)/CH (8)	−0.0649
CH_3 (5)	−0.0114	CH (5)/CH (6)	0.0396
C (4)	−0.1368	C (4)	−0.103
C (1)	0.3392	C (1)	0.3551
O (2)	−0.5792	O (2)	−0.5687
O (3)	−0.5811	O (3)	−0.5687

[a] Numbers in parentheses refer to Scheme 1.



Pivalate ion Benzoate ion

Scheme 1.

between physical interaction quantities. In most of these analyses, the differential quantities such as $\delta\Delta H^{\ddagger}_{obs}$ and $\delta\Delta S^{\ddagger}_{obs}$ have been the functions of interest, in which the effect of experimental error might be accentuated in comparison with the absolute quantities, $\Delta H^{\ddagger}_{obs}$ and $\Delta S^{\ddagger}_{obs}$. Hence the solvation numbers for nucleophiles might well be an artifact of the assumption.

The empirical correlation between the two quantities pertinent to a specific interaction, *i.e.* $-\Delta H_{t,SI}^{AN\rightarrow MeOH}$ and *Z* (Nu^-), is given in Figure 3. The slope value, which is equivalent to the averaged value of the enthalpy change, ΔH_{SE}, over a wide range of nucleophiles, *i.e.*, aliphatic and aromatic amines and corresponding carboxylate ions, amounts to *ca.* −11 kJ mol^{-1}. The solvation numbers for anionic nucleophiles have been derived from work on the Finkelstein-type reactions under the assumption $Z(TS^-) = 1$, whereas those for neutral nucleophiles were derived through work on the Menschutkin-type reactions without recourse to that assumption.[10,11] Thus it should be noted that the two quantities which are subject to mutually independent experimental, as well as theoretical restraint, seemingly fall into one correlation.

A rather weak specific interaction for pyridine and imidazole derivatives makes it difficult to differentiate between systematic errors ascribable to the possibly erroneous assumption, $Z(Nu^-) = 1$, for some pyridine derivatives, and experimental random errors.[10,11,14] A rather wider random distribution of data around the regression line (Figure 3) could easily accommodate small systematic errors.

When back-calculated from the correlation, the near-constancy of the specific interaction enthalpy for the transition-state anions, $\Delta H_{t,SI}^{AN\rightarrow MeOH}(TS^-)$ *ca.* −10.5 kJ mol^{-1}, leads to the conclusion that $Z(TS^-) = 1$ throughout for the transition-state anions. This also tends to confirm the consistency of our treatment.

The largest number of methanol molecules hydrogen-bonded to one oxygen atom amounts to 1.85 (*i.e.* 3.7/2) at adamantane-1-carboxylate ion and is supposed to increase with increased basicity of anion (see Figure 3). This observed value is not unreasonable, considering that the evaluation from fractionation factor studies that three methanol molecules are hydrogen-bonded to methoxide ion in methanol,[15,16] and the fact that methoxide ion is highly basic compared with carboxylate ion.

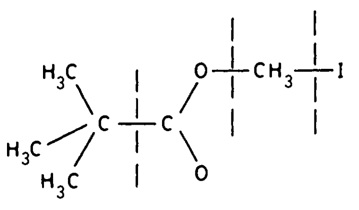
The trend shown in Figure 3 makes the general chemical sense that the basicity of a compound, (X) as expressed by the quantity, $\Delta H_{t,SI}^{AN\rightarrow MeOH}$ [(X)], and the number of methanol molecules hydrogen-bonded to it are mutually dependent quantities, with a coefficient of transformation *ca.* −11 kJ mol^{-1} molecule^{-1}.

AM1 molecular-orbital calculations have been performed to examine the relevance of the notion derived from the discussion on physical interaction enthalpy, $\Delta H_{t,SI}^{AN\rightarrow MeOH}$, *i.e.* sensible or unlikely electronic reorganization on activation according to the participation of aromatic or aliphatic carbon moiety in the nucleophile, as regards the view based on model calculation.

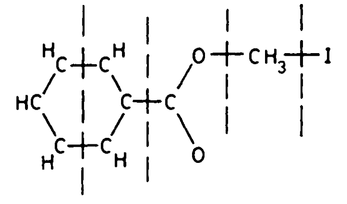
In order for the main features to be extracted from the comparison of experimental results with calculated details, it is useful to gather together some of the calculations. Thus, some part of the AM1 atomic charges are summed to give group charges, and are summarized in Table 4. (The numbers in parentheses in Table 4 indicate the atom or group number given in Scheme 1).

Three methyl groups in pivalate ion and two *ortho*-CH groups in benzoate ion occupy a position comparable to the anionic centre; the remaining (*meta-* and *para-*) CH groups in benzoate ion have no counterpart in pivalate ion. A small amount of negative charge is found on the three methyl groups in pivalate ion, whereas the CH-groups in benzoate ion, *i.e.*, CH(5) and CH(6), are positively charged, and a significant amount of negative charge is distributed over the *meta-* and *para-*CH groups. Thus, with pivalate ion as a reference (unit of negative charge), benzoate ion would be approximated as a superimposition of a dipole on unit negative charge (*i.e.*, pivalate ion) with the negative end of the dipole being located somewhere around *meta-*and *para-*CH groups. This approximation is equivalent to the idea of the induction of dipole through π-conjugative interaction between CO_2 and phenyl groups as discussed above.

The concept of group contribution to an electronic reorganization of activation for a group, X, $(GCERA)_X$, as



Transition-state anion (Pivalate + MeI)



Transition-state anion (Benzoate + MeI)

Scheme 2.

Table 5. Group contributions to electronic reorganization on activation.

Pivalate + CH_3I		Benzoate + CH_3I	
Group	Contribution	Group	Contribution
$(CH_3)_3C$	0.1473	$(CH)_3$	0.0937
CO_2	0.2090	$(CH)_2C$	0.0569
CH_3	0.4247	CO_2	0.2381
I	−0.7810	CH_3	0.4367
		I	−0.8253

$$(\mathrm{GCERA})_X = \mathrm{GC}(\mathrm{TS}^-)_X - \mathrm{GC}(\mathrm{Nu}^-)_X \qquad (8)$$

$$(\mathrm{GCERA})_X = \mathrm{GC}(\mathrm{TS}^-)_X - \mathrm{GC}(\mathrm{CH_3I})_X \qquad (9)$$

defined by equations (8) or (9) is a convenient way of understanding the molecular origin contributing to such physical interaction quantities as $\delta\Delta H^{\ddagger}_{\mathrm{Phys}}$, $\delta\Delta S^{\ddagger}_{\mathrm{Phys}}$, and $\delta\Delta G^{\ddagger}_{\mathrm{Phys}}$; where $\mathrm{GC}(\mathrm{TS}^-)_X$, $\mathrm{GC}(\mathrm{Nu}^-)_X$, and $\mathrm{GC}(\mathrm{CH_3I})_X$ represent for the sum of the AM1 atomic charge over the relevant atom or atoms contained in the group, X of the transition-state anion, of the nucleophile, and of methyl iodide, respectively. The splitting of molecules into relevant groups is indicated by dashed lines in Scheme 2, and the corresponding values are summarized in Table 5.

The numerically larger charge on the iodine atom in the benzoate ion reaction indicates that more negative charge develops on the incipient iodide ion for the benzoate ion reaction than for the pivalate ion reaction. In other words, the transition state for the benzoate ion reaction is located further along the reaction co-ordinate than that for the pivalate ion reaction. This conclusion gives a molecular interpretation for the different behaviour of $\delta\Delta H^{\ddagger}_{\mathrm{Phys}}$ values for the two reactions, as well as that from Bordwell's observation.[13]

For the benzoate ion reaction, a larger amount of positive charge develops on the *meta-* and *para*-CH groups [$(CH)_3$ group in Table 5] accompanying activation, than on the group including two *ortho*-CH groups and α-carbon [$(CH)_2C$ group in Table 5]. The phenomenon is equivalent to the shift of electrons over a long distance on activation. In other words, *meta-* and *para*-CH groups in the phenyl ring will play a role as an electron pool during the reaction. In contrast, for the pivalate ion reaction, although nearly the same amount of positive charge develops on the hydrocarbon moiety during activation as for benzoate ion reaction, *i.e.*, 0.1473 for the former and 0.1506 (= 0.0937 + 0.0569) for the latter, the charge is buried in the steric bulk of hydrocarbon moiety.

The amount of positive charge developed on activation, and the degree of shielding of the charge by the hydrocarbon moiety, which affects the accessibility of surrounding solvent molecules to the electron-reorganizing sites, will be responsible for the different trends in the quantities, $\delta\Delta H^{\ddagger}_{\mathrm{Phys}}$, $\delta\Delta S^{\ddagger}_{\mathrm{Phys}}$, and $\delta\Delta G^{\ddagger}_{\mathrm{Phys}}$ between aliphatic and aromatic carboxylate ions.

Experimental

Materials.—Acetonitrile was successively distilled from calcium hydride, phosphorus pentaoxide, and again from calcium hydride. Methanol was distilled from the mixture after it had been refluxed with magnesium metal, and then twice distilled under a nitrogen atmosphere. Ethyl iodide was shaken with a dilute potassium carbonate solution, washed with water, dried over calcium chloride for one day, and distilled. Tetra-alkylammonium salts were prepared and purified as described.[7]

Kinetics.—Kinetic measurements were carried out as described previously.[11] Rate constants were determined at three or four of the following temperatures, 0.0, 10.0, 20.0, 30.0, 40.0, and 50.0 °C. Experimental error was estimated to be 2% from duplicate or triplicate runs.

Calculations

AM1 molecular-orbital calculations were performed using the AMPAC program[17] for pivalate and benzoate ions, and for the transition-state anions from the relevant nucleophile with methyl iodide. In order to reduce the computational time, a geometry optimization was carried out with the following symmetry restrictions being imposed, that the $O–CH_3–I$ moiety and t-butyl group maintain C_{3v} symmetry, and phenyl group possesses C_{2v} symmetry throughout the reaction. The geometry which gives the maximum energy under these symmetry constraints, was taken to be an activated complex, and no more internal co-ordinates were optimized.

Acknowledgements

Molecular-orbital calculations were carried out on a NEAC SX-2N computer at the Computation Centre, Osaka University. We are grateful to Dr. M. H. Abraham, University College London, for valuable discussions.

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