base. All standard solutions were referred to potassium acid phthalate as the primary standard. Since the standardizations were carried out at room temperature, and the alcoholic base for saponification was pipetted at 0°, a satisfactory correction for the increase in concentration of the solution due to contraction was made by multiplying M by $(0.806/0.785) = 1.0268$, the ratio of the densities of the solvent at the two temperatures.

The Linear Enthalpy-Entropy Effect

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A limitation to the Compensation law or the linear enthalpy-entropy relationship as previously proposed by us whereby membership in a family of closely similar structure was required in order for the law to hold has been explored by consideration of data on esterification, hydrolysis, ionization, free radical, displacement, and other reactions as well as on solvent effects and salt effects. The limitation has broadened the applicability of the law and emphasized the relative invariance of the slope of the linear equation and the additivity of the differences in the intercepts. The implications of the relationship are discussed briefly.

In a previous paper[1] a restriction to the commonly accepted method[2] of correlating enthalpy of activation with entropy of activation was suggested whereby the linear relationship, equations 1 and 2,

$$\Delta H^* = \Delta F_0^* + \beta_0 \Delta S^* \qquad (1)$$

$$\Delta F^* = \Delta F_0^* + (\beta_0 - T)\Delta S^* \qquad (2)$$

was applied only to families of closely related structures, each family having a characteristic value of ΔF_0^* (the intrinsic free energy of activation).[3] Furthermore, all the families had a common slope, $\beta_0 = 277°$, for a specific reaction, as illustrated by the parameters for the saponification of the ethyl esters of halogen-substituted phenoxyacetic acids. The conditions for membership in a given family were shown to be of a subtle nature by the formation of four families, the parent ester, the 2-halogen-substituted esters, the 4-halogen-substituted esters, and the 2,4-dihalogen-substituted esters. Here we wish to report that the relationship seems to be quite general, being applicable to cases which did not fit the more general method[4] of attempting to adjust a single regression line for all substituents relating the enthalpy to the entropy for a reaction. Also, the slope, β_0, does not appear to vary very much reaction to reaction and may well be a constant or a multiple of a constant such that equations 1 and 2 may be universally applicable.

Before proceeding with an examination of the data in the literature it should be made clear that the assumption has been made that such data fit the simple Arrhenius equation, $\ln k = \ln A - (E_a/RT)$, with both $\ln A$ and E_a being independent of temperature.[5,6] A modified form of the Arrhenius equation exists which contains the added term $(C/R)\ln T$ in which C is the heat capacity at constant pressure.[7] However, this added term can only be evaluated from the curvature of the $\log k$ *vs.* $(1/T)$ plot which is seldom observed if the range and number of temperatures used is small. With the Arrhenius parameters in hand, it is also assumed that $\Delta H = E_a - RT$ and that $\Delta S = 2.303\ R\ (\log A - \log k/h - \log T - 1/2.303)$. With these provisos, it is easily shown that if E_a is plotted against $\log A$, the slope of the family line is $2.303\ R\beta_0$. For the reverse plots, ΔS *vs.* ΔH and $\log A$ *vs.* E_a the resulting slopes are the reciprocals of β_0 and $2.303\ R\beta_0$.

Although many studies have been carried out on the effects of substituents on the rates and equilibria of reactions at a given temperature, not all investigators have studied the effect of temperature variation. A far from exhaustive search of the literature showed that many results were not suitable for examination for classification into families because the variation of structure of the substituents was too drastic. On the other hand, the data from the work of Hartman and collaborators[8] as well as that from Smith and Hurley[9] for the esterification

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[1] R. F. Brown and H. C. Newsom, *J. Org. Chem.*, **27**, 3010 (1962).

[2] J. E. Leffler, *ibid.*, **20**, 1202 (1955).

[3] The intrinsic free energy of activation also may be regarded as a standard state, the specification for such a standard state being that ΔS^* be zero or that the intrinsic free energy of activation be equal to the intrinsic enthalpy of activation. Because the terminology is clumsy and because no loss of clarity will be caused, the adjectival phrase "of activation" and the asterisk * will be dropped in the subsequent usage in this paper. When equilibria are considered the context for the shift to the thermodynamic entities should be clear.

[4] The general linear enthalpy-entropy effect has been noted not only for rates of homogeneous and heterogeneous reactions but also in diffusion, viscosity, electron emission, equilibria of all types, conductivity, and solvent effects, and has been called the Compensation Law.[47]

[5] Recently a tendency to report $\ln A$ or $\log A$ as $\ln pZ$ or $\log pZ$ has occurred even though the latter is a function of T as shown by $\Delta \log pZ = 0.5\ \Delta \log T$ from the collision rate theory.[6]

[6] A. A. Frost and R. G. Pearson, "Kinetics and Mechanism," J. Wiley and Sons, Inc., New York, 1953, p. 65.

[7] S. W. Benson, "The Foundations of Chemical Kinetics," McGraw-Hill Book Co., Inc., New York, 1960, pp. 66–75.

[8] R. J. Hartman and A. M. Borders, *J. Am. Chem. Soc.*, **59**, 2107 (1937); R. J. Hartman, L. B. Storms, and A. G. Gassman, *ibid.*, **61**, 2167 (1939); R. J. Hartman and A. G. Gassman, *ibid.*, **62**, 1559 (1940); A. G. Gassman and R. J. Hartman, *ibid.*, **63**, 2393 (1941).

[9] H. A. Smith and R. B. Hurley, *ibid.*, **72**, 112 (1950).

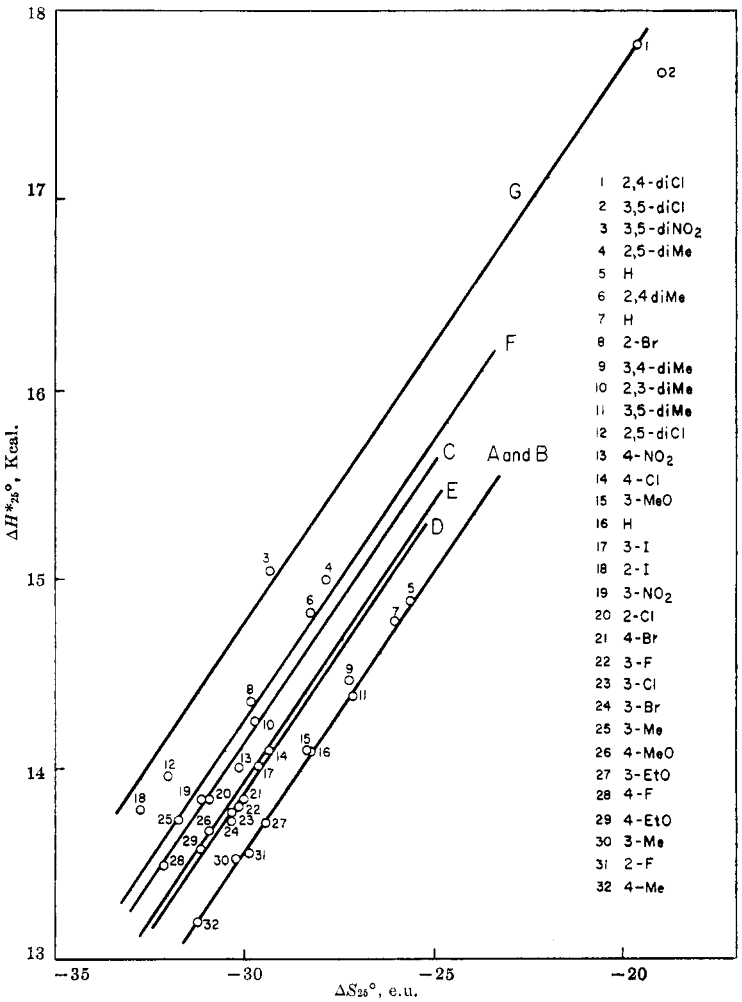

Fig. 1.—Plot of $\Delta H^*_{25°}$ against $\Delta S^*_{25°}$ for the esterification of substituted benzoic acids catalyzed by hydrogen chloride in methanol.[8,9] The lines are drawn with slope β_0 = 295°.

of substituted benzoic acids in methanol catalyzed with hydrogen chloride were recalculated in order to obtain E_a, log A, ΔH, and ΔS to extra decimal places and the results are displayed in Fig. 1. This reaction does not follow the Hammett relationship[10]; neither does it give a good general enthalpy-entropy relationship. But upon inspection seven families were picked for testing by tentative selection for a rough graphical fit to a slope of 300°. Group A contained three values for benzoic acid obtained at different times by different workers and the substituents 3-Me, 3-MeO, 3-EtO, and 3,5-diMe. The seven points gave a regression line with β_0 = 310° and ΔF_0 = 22.84 kcal. Group B consisted of only two points, 4-Me and 3,4-diMe, which gave β_0 = 318° and ΔF_0 = 23.14 kcal. Group C consisted of the *ortho*-halogens which scattered widely in this case and gave β_0 = 84°. Group D consisted of the *meta*- and *para*-halogens which gave β_0 = 209° a low value since 4-fluoro was above the line. Omitting this point gave β_0 = 366°, which seemed excessive. Group E, 4-MeO and 4-EtO, gave β_0 = 379°; group F, 2,3-, 2,4-, and 2,5-diMe, gave β_0 = 377° and group G, 2,4- and 2,5-diCl, gave 310°. Omitting the *ortho* halogen group and including 4-fluoro, a weighted average gave β_0 = 295°. This value of the slope gave ΔF_0 equal to 22.40, 22.40, 22.99, 22.73, 22.77, 23.09, and 23.59 kcal., respectively for the seven groups. The lines in Fig. 1 were drawn to fit these intercepts and the averaged slope. Families A and B coalesce and so do D and E. Thus substitution of *meta*- or *para*-methyl (perhaps generalized to alkyl?) or of *meta*-alkoxy in benzoic acid may be regarded as insufficient to cause a change to another family. Substitution of a halogen either *meta* or *para* or of alkoxy in the *para*-position produce another family. Now if the ΔF_0 values for the families have an additive relationship, the effect of multiple substitution[1] should be predictable. Thus 3,4- and 3,5-dimethyl substitutions should have no effect on ΔF_0 and they should be found in the same family as the parent and they were. Likewise, *ortho*-methyl substitution increased ΔF_0 by about 0.7 kcal., but further substitution by methyl in the *meta*- or *para*-positions

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(10) H. H. Jaffe, *Chem. Rev.*, **53**, 191 (1953), for Reaction No. 40 gives r = 0.4 to 0.45.

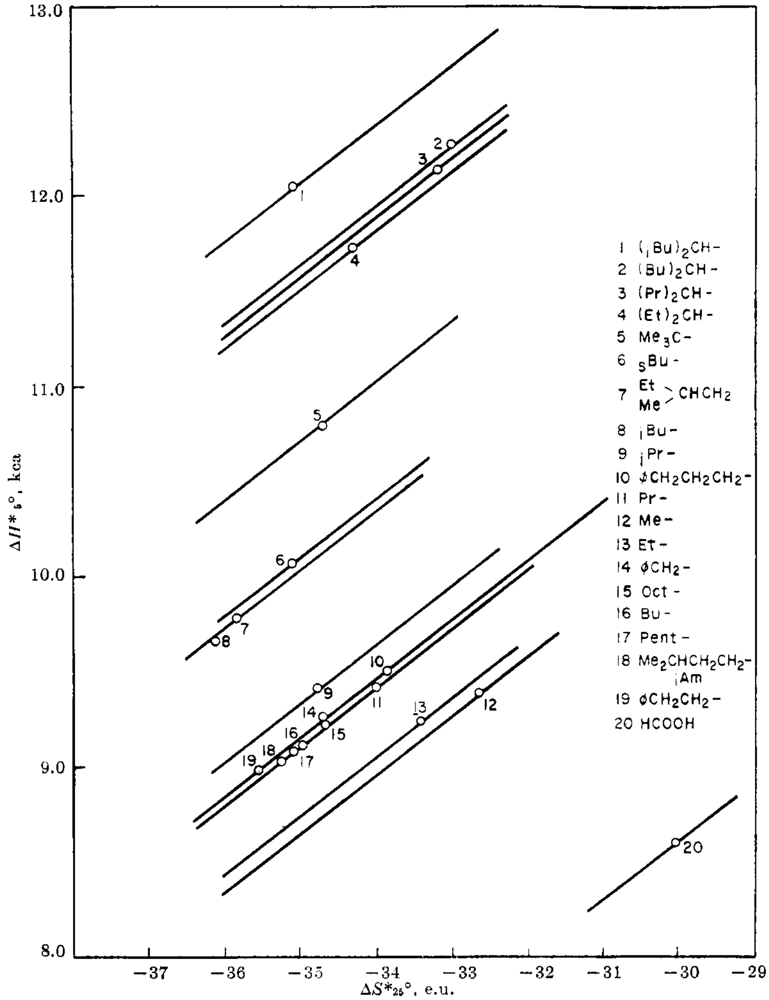

Fig. 2.—Plot of $\Delta H^*_{25°}$ against $\Delta S^*_{25°}$ for the esterification of aliphatic acids, RCOOH, in methanol catalyzed by hydrogen chloride.[11] The lines are drawn with slope $\beta_0 = 310°$.

should have had no effect and this was found to hold for the 2,3- and 2,4- and 2,5-dimethylbenzoic acids. Substitution of *meta-* or *para*-halogen increased ΔF_0 by 0.3 to 0.4 kcal. so that further substitution to form a 3,4- or 3,5- dihalogen acid should have produced a family with an increase in ΔF_0 of about 0.6 to 0.8 kcal. Only one point was available to test this, the 3,5-dichloro, and it was found to be about 0.9 kcal. above the parent line. Despite the scatter of points, an *ortho*-halogen increased ΔF_0 by about 0.6 kcal. Combining this value with that for a halogen in the *meta-* or *para*-position, the ΔF_0 for 2,3-, 2,4-, and 2,5-dihalogen substitution should have been about 1.0 kcal. higher. The point for 2,4-dichlorobenzoic acid was found to be 1.2 kcal. higher, and for the 2,5-dichloro isomer about 1.0 kcal. The point for *meta*-nitro was found in group C although it is hard to imagine such a substituent having much in common with *ortho*-halogens. At any rate, *meta*-nitro caused an increase in ΔF_0 of 0.6 kcal. so that 3,5-dinitro should have had an increase of 1.2 kcal., found 1.4 kcal. The only remaining points were the two *ortho*-alkoxy groups which seemed to lie on a line about 0.8 kcal. below the parent line. That ΔF_0 could be predicted for multiple substitution even though an *ortho* substituent be involved seemed to be a safe assumption. However, the direction and magnitude of the changes were seen to be a characteristic of the reaction, as shown by an increase in ΔF_0 of about 0.4 kcal. in acid catalyzed esterification of benzoic acids but a decrease of about 0.3 kcal. in the saponification of ethyl phenoxyacetates[1] for *para*-halogen substitution.

The data of Smith[11] were recalculated for the esterification of aliphatic acids in methanol catalyzed by hydrogen chloride and the results shown in Fig. 2. The points gave a very rough general enthalpy-entropy correlation. But on looking for family relationships it was seen that if R in RCOOH were Pr, Bu, Am, *i*-Am, Oct, $C_6H_5CH_2$, C_6H_5-CH_2CH_2, or $C_6H_5CH_2CH_2CH_2$ a family with $\beta_0 = 310°$, $\Delta F_0 = 19.95$ kcal. existed. Applying

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[11] H. A. Smith, *J. Am. Chem. Soc.*, **61**, 254, 1176 (1939); **62**, 1136 (1940).

this slope to the point for formic acid gave ΔF_0 = 17.90 kcal.; for acetic and propionic acids, 19.55 kcal.; for isobutyric acid, 20.20 kcal.; for R = *i*-Bu or active Am (2-methylbutyl), 20.85 kcal.; for *s*-Bu, 20.95 kcal.; for *t*-Bu, 21.55 kcal.; for diethyl, dipropyl, and dibutylacetic acids, 22.40 kcal.; and for diisobutylacetic acid, 22.90 kcal. Beginning with formic acid, substitution of methyl or ethyl for H gave an increase of 1.65 kcal. in ΔF_0, or the first substitution of alpha-methyl in acetic acid was without effect. Substitution of propyl or a longer chain produced an increase of 2.05 kcal. with reference to formic acid, or looked at in another way, the first beta-methyl group in a chain caused an increase of 0.40 kcal.

Returning to the effects of alpha-methyl substitution, going from acetic to propionic to isobutyric to pivalic acid produced increases of zero, 0.65, and 1.35 kcal. in ΔF_0, or if the molecular weight were kept constant, the increases in going from R = Bu to *s*-Bu to *t*-Bu were 1.0 and 0.60 kcal. The effect of beta-methyl was shown by an increase of 0.40 in going from propionic to butyric acid, and by 0.90 in going from pentanoic to 3-methylpentanoic acid. Going from R = *i*-Pr to *s*-Bu, 0.75, should have been the same as going from Et to Pr, 0.40. Replacing the methyls in R = *i*-Pr one at a time with ethyls gave increases of 0.75 and 0.55. Further lengthening of the two chains produced no further effect although diisobutylacetic acid with two beta isopropyl groups (or four gamma methyls) was still higher by another 0.50 kcal. although a single gamma methyl as typified by R = *i*-Am had zero effect as compared to the other long chain acids. It was interesting to note that substitution of phenyl in acetic acid produced the same effect as an ethyl or larger group, or phenyl in the beta position of propionic acid the same effect as any alkyl group, and was without effect in the gamma position. On the other hand, substitution of phenyl for H in formic acid produced a major change which was calculated by assuming a common slope of 300° in order to calculate intercepts not subject to convergence of the lines during extrapolation of ΔS = zero. This gave $\Delta F'_0$ for formic acid equal to 17.60 kcal. and $\Delta F'_0$ for benzoic acid (from Fig. 1) of 22.55 kcal. or an increase of 4.95 kcal.[12] These two long series of data for a single reaction illustrate the constancy of β_0 and the additivity of differences in ΔF_0 although with a large uncertainty as yet in the aliphatic cases.

Other data on reactions concerned with esters may be summarized more briefly. The work of Davies and Evans[13] is comparable to that of Smith[11] terification of substituted benzoic acids in cyclo- and is not as extensive. The acid-catalyzed es- hexanol[14] showed β_0 = 325° for the parent acid, 3-Me, 3-Cl, 4-Cl, 3-Br, and 3-NO_2. The hydrochloric acid-catalyzed hydrolysis of aliphatic ethyl esters in aqueous acetone[15] separated into families as already shown for the esterification reaction, although the list of substituents was much shorter. For R = $C_6H_5CH_2$—, $C_6H_5CH_2CH_2$—, $C_6H_5CH_2CH_2CH_2$—, and $C_6H_5(CH_2)_4$—, β_0 was 330° and ΔF_0 was 24.95 kcal. The saponification of esters in aqueous ethanol for the aliphatic acids[16] gave β_0 = 339° and ΔF_0 = 22.12 kcal. for the family butanoic to octanoic acids. Here acetic and propionic acids were separated in ΔF_0 by about 0.3 kcal., and R = *s*-Bu seemed to be seriously out of place by being about 0.2 kcal. below the general long chain family as compared to being about 1.0 kcal. above in Fig. 2. The saponification of substituted ethyl benzoates in aqueous ethanol[17] showed a peculiarity in that except for 2-methyl, 2-chloro, 2-nitro, and 3-nitro, the data[16,17] indicated a relatively constant ΔS of about −16 e.u., which meant that practically every substituent used caused the formation of a new family. The *meta*- and *para*-halogens were bunched together except for 4-fluoro and 3-chloro at ΔH = 16.2 kcal. The curious results of Herbst and Jacox,[18] which gave ΔH about 3 kcal. less and ΔS about 11 e.u. more negative than previous data,[16,17] nevertheless fitted a line of 295° slope between the points for ethyl benzoate and for ethyl 4-methylbenzoate! By application of a slope of 300° to a plot of their data[18] a separation into families occurred (all substituents were in the *para*-position) of methyl and ethyl, with propyl and isopropyl about 0.1 kcal. higher and with butyl, *sec*-butyl and *tert*-butyl another 0.1 kcal. higher still and the two amyl groups up another 0.1 kcal. in ΔF_0. Except for methyl and ethyl this looked as though the type of alkyl group substitution was of less effect on ΔF_0 than the molecular weight of the group. Before leaving the alkaline alcoholic reactions mention should be made of the work[19] on the 4′-substituted biphenic acid esters. Although the list of substituents was so small that only 4′-chloro and 4′-bromo gave a family of more than one member, these two differed only by 0.10 in ΔH but gave a slope of 310°!

In aqueous acetone, the alkaline hydrolysis of substituted ethyl benzoates showed the same general features as demonstrated above. Although

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[12] Such a minor change in slope produces but slight changes in the relative values of ΔF_0 as shown by a $\Delta F'_0$ of 21.20 kcal. for trimethylacetic acid—for example, a decrease of 0.35 as compared to a decrease of 0.30 kcal. for formic acid despite a difference of almost 5 e.u. in ΔS for the two acids.

[13] G. Davies and D. P. Evans, *J. Chem. Soc.*, 339 (1940).

[14] R. J. Hartman, L. B. Storms, and A. G. Gassman, *J. Am. Chem. Soc.*, **61**, 2167 (1939).

[15] H. A. Smith and J. H. Steele, *ibid.*, **63**, 3466 (1941); H. A. Smith and R. R. Myers, *ibid.*, **64**, 2362 (1942).

[16] E. A. Moelwyn-Hughes, "Kinetics of Reaction in Solution," Clarendon Press, Oxford, 1947, p. 141 and p. 149; H. A. Smith and H. S. Levenson, *J. Am. Chem. Soc.*, **61**, 1172 (1939); H. S. Levenson and H. A. Smith, *ibid.*, **62**, 1556, 2324 (1940).

[17] See ref. 16; also D. P. Evans, J. J. Gordon, and H. B. Watson, *J. Chem. Soc.*, 1430 (1937).

[18] R. L. Herbst, Jr., and M. E. Jacox, *J. Am. Chem. Soc.*, **74**, 3004 (1952).

[19] E. Berliner and L. H. Liu, *ibid.*, **75**, 2417 (1953).

Price and Lincoln[20] differ from Tommila and Hinshelwood[20] in the rates and in the parameters for both the 3-methyl- and the 4-methylbenzoic esters, the slopes through the corresponding points were 281° and 282° with increases in ΔF_0 of about 0.3 and 0.5 kcal. over the unsubstituted ester. This placed *meta*-methyl into a separate family which in this case also included *meta*-amino and *meta*-dimethylamino. The corresponding *para*-substituents all separated into different families. Some inconsistencies were noted such as that 4-isopropyl wandered down into the family of *meta* substituents and that *meta*-*tert*-butyl was above the line for *para*-alkyls. Of the three disubstituted esters only 3-amino-4-methyl followed the rule of additivity of ΔF_0 although 3-dimethylamino-4-methyl was not far off.

For variation of the alkyl moiety in esters we examined only one set of data[20] and since the list of substituents was short for the saponification of benzyl acetates and phenyl acetates, all the points separated into different families. The separation followed the same patterns as already shown for variations in the acyl group. For the hydrolysis of anhydrides, again only one paper[21] was examined, the solvolysis of substituted benzoic anhydrides in 75% aqueous dioxane. Again the list of substituents was small and the usual separation occurred into one point per family except that 3-methoxy differed from the parent only by about 0.1 to 0.2 kcal. in ΔF_0 on the assumption that β_0 was 300°. Likewise, *meta*-methyl was 0.4 kcal. above and *para*-methyl and *para*-*tert*-butyl (same family?) was 0.7 kcal. above the parent. This system should be thoroughly investigated since the differences in rates and parameters become sizable enough for good separation.

As an example of the Menschutkin reaction we used the results of Berliner and Monack[22] on the reaction of piperidine with *para*-substituted 2-nitrobromobenzenes in piperidine as the solvent. Application of a slope of 300° to a plot of the data showed that the halogens (except for fluorine) formed a family at 1.1 kcal. below the parent unsubstituted compound, that methyl and *t*-butyl formed a family of 1.1 kcal. above the parent, and that methoxy and ethoxy formed a family up another 1.3 kcal., while dimethylamino, hydroxy, and amino gave single points up another 1.6, 0.4, and 1.2 kcal. respectively in ΔF_0.

For free radical reactions, Denisov[23] with data from the literature has plotted log A against E_a for six different reactions for the general enthalpy-entropy relationship and obtained slopes[24] varying between 0.08 and 0.6 kcal.$^{-1}$. Examination of his published graphs showed that a separation into families probably was occurring but the substituents used were such that few if any polymembered families existed in the data. However, single points fell into the familiar pattern already shown in Fig. 2. Unfortunately the extensive work of Bartlett and collaborators[25] on the decomposition of *tert*-butyl peresters and various peroxyoxalates does not contain the proper substituents to allow a separation into families with more than one member. However, the point for *m*-methoxyphenylacetyl was only 0.3 kcal. in ΔF_0 above the parent if the usual assumption of β_0 = 300° were made.

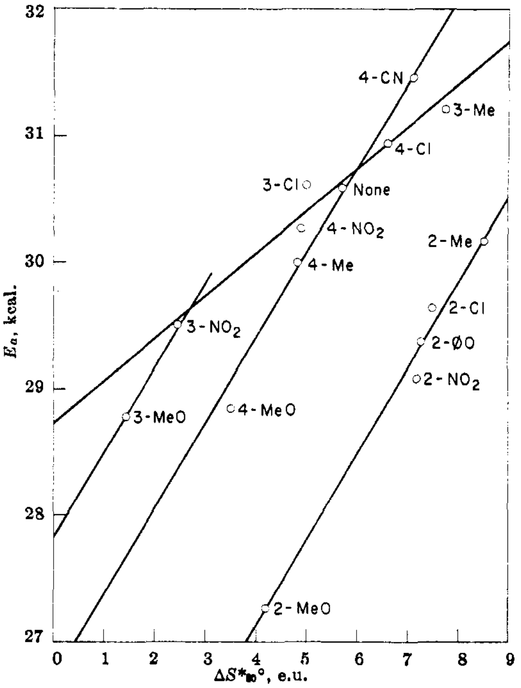

Fig. 3.—Plot of E_a against ΔS^* for the thermal dissociation of *sym*-substituted benzoyl peroxides in acetophenone.[26] The lines are drawn with slopes of 336 and 673°.

An interesting exception to the usual pattern was found in the plot of the data for the thermal cleavage of *sym*-substituted benzoyl peroxides in acetophenone[26] given in Fig. 3. The regression

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[20] E. Tommila and C. N. Hinshelwood, *J. Chem. Soc.*, 1801 (1938); C. C. Price and D. C. Lincoln, *J. Am. Chem. Soc.*, **73**, 5836, 5838 (1951).

[21] E. Berliner and L. H. Altschul, *ibid.*, **74**, 4110 (1952).

[22] E. Berliner and L. C. Monack, *ibid.*, **74**, 1574 (1952).

[23] E. T. Denisov, *Izv. Akad. Nauk S.S.S.R., Otd. Khim. Nauk*, No. **7**, 1298 (1960) (*Bull. Acad. Sci. U.S.S.R., Div. Chem. Sci.*).

[24] For β_0 = 300°, the corresponding slope would be 0.75 kcal.$^{-1}$.

[25] P. D. Bartlett and R. R. Hiatt, *J. Am. Chem. Soc.*, **80**, 1398 (1958); P. D. Bartlett and C. Ruchardt, *ibid.*, **82**, 1756 (1960); P. D. Bartlett and R. E. Pincock, *ibid.*, **82**, 1769 (1960).

[26] A. T. Blomquist and A. J. Buselli, *ibid.*, **73**, 3883 (1951). A plot of E_a *vs.* ΔS_{80}° as given in their Table III, made little sense until the parameters for the bis(3,5-dinitro)benzoyl peroxide were recalculated from the temperatures and rate constants given in the table The recalculated values, E_a = 41.42 kcal. and ΔS_{80}° = 34.80 e.u., were so different from the tabulated values of 31.2 kcal. and 5.8 e.u. that an error must have occurred in tabulating the rate constants. Thus, if $k_{\text{min}^{-1}} \times 10^3$ at 80.0° tabulated as 1.12, was raised to 2.12, then 30.18 kcal. and 2.96 e.u. were calculated, a much more reasonable result, although still at variance with the tabular values. Thereupon, E_a and ΔS_{80}° were recalculated from the given values of k and T for all the compounds given in Table III; $k \times 10^3$ for bis(4-methyl)-benzoyl peroxide at 73.36° tabulated as 16.80 was taken as 1.68. Our calculations of E_a by least squares agreed to within 0.1 kcal. for seven of the sixteen compounds, differences of up to 1.1 kcal. occurring among the rest. For ΔS_{80}° the differences ranged from 0.1 to 3.0 e.u. The revised values were used in Fig. 3.

line calculated for the five *ortho* di-substituted compounds had a slope of 674°, and that for the five *para* di-substituted compounds and the unsubstituted parent had a slope of 672°. Using the average slope of 673°, the intercepts were 24.44 and 26.69 kcal., respectively. Using the slope and intercepts, E_a was recalculated for each substance from the ΔS_{80° values. The results had an average deviation of only ±0.08 kcal. for the *ortho* and ±0.13 kcal. for the *para* disubstituted compounds. In these instances, all substituents in a given position on the ring grouped into a family with a β_0 approximately twice that of all previous observations. Perhaps the increased sensitivity of E_a (or ΔH^*) to ΔS^* for this particular reaction was caused by the disubstitution coupled with a symmetrical homolytic transition state. Partial support for this explanation was furnished by the location of the parent compound in the more symmetrical *para* family. On the other hand such an explanation did not account for the eccentric locations of the points for the *meta* compounds, the regression line for which (including the parent but excluding the bis(3-methoxy)benzoyl peroxide) had $\beta_0 = 320°$, or roughly one half of 673°. Using 336°, the intercept was 28.72 kcal., and recalculation of E_a as described above gave an average deviation of ±0.10 kcal., which would have decreased to ±0.02 kcal. if the 3-Cl point had fitted better. As may be seen, the 3-MeO point deviates from this line by 0.43 kcal., but a line of slope 673° and intercept 27.82 kcal. fits the 3-MeO and the 3-NO_2 points within ±0.02 kcal.! Whether there is an inflection point at 3-NO_2 must await reinvestigation of this cleavage of benzoyl peroxides.

For ionizations the data of Papee and co-workers[27] on the thermodynamic functions for the aqueous ionization of substituted phenols were handled in two ways. First it was assumed that two families were represented, the parent with the 3- and 4-methyl- and the 3,4- and 3,5-dimethylphenols in the one and the 2-methyl- with the 2,3-, 2,4-, 2,5-, and 2,6-dimethylphenols in the other. The use of least squares gave a β_0 of 281° for the first family, 268° for the second family, or an average of 274° which was used to calculate ΔF_0 of 13.23 and 13.55 kcal., respectively, for the two groups. Recalculation of the ΔH values from the observed values of ΔS by the use of these parameters gave an average deviation of ±0.12 kcal. from the experimental values. Second all ten points were treated as a single group with $\beta_0 = 279°$ and a ΔF_0 of 13.50 kcal. The use of this slope and intercept gave an average deviation of ±0.18 kcal. when ΔH was recalculated, so that no distinction was justified in this instance. However, Fernandez and Hepler[28] found a negative slope for the general relationship in their study on the ionization of 2- and 4-chloro- and 2-, 3-, and 4-nitrophenols. This again is a case of each point belonging to a separate family which may be verified when sufficient data for family groupings becomes available. Hepler and O'Hara[29] also have used the data of Papee *et al.*[27] and plotted $\Delta H/(\nu_s^2 - \nu_u^2) = a + (b\Delta S)/(\nu_s^2 - \nu_u^2)$ which is equivalent to (1) in that $b = \beta$. Their method gave 9 points with a slope of 284°, only 5° higher than our 279° for 10 points.

Papee and group[30] have made a similar study of the ionization of anilines with the same substituents. The scatter of points was worse than with the phenols as shown by β_0 of 269° and 294° for separation into the two families described above. Use of an adopted slope of 294° gave ΔF_0 values of 6.61 and 6.22 kcal. which differed by 0.39 as compared with 0.32 kcal. for the phenols. Recently, Biggs[31] measured pK for phenol and aniline as well as the *o*-, *m*-, and *p*-fluoro-, chloro-, bromo-, iodo, methyl-, methoxy-, and nitroanilines. His graph of ΔH *vs.* ΔF gave the rough linear general relationship, but examination of his published graph showed the separation into families with slope close to infinity as they should for such a graph.[1] The *o*-halogens formed a group (with the exception of *o*-fluoro), the *m*-halogens a second family, the *p*-halogens a less distinct family (again fluoro is an exception), the *m*-methyl and *m*-methoxy came close to forming a family with the parent, while the other substituents gave the familiar distribution of single point families. The data for the *m*-halogenoanilines were recalculated (ΔH_{25° = 5.939, 5.451, 5.369, and 5.695 kcal.; ΔS_{25° = 3.57, 2.14, 1.85 and 2.67 e.u. for F, Cl, Br and I) which gave $\beta_0 = 338°$ and $\Delta F_0 = 4.758$ kcal. Using the parameters and the given ΔS, ΔH was recalculated to give 5.956, 5.472, 5.374, and 5.652 kcal., average deviation ±0.022, which would have been even less if the *m*-iodo point had agreed better.[32]

Solvent effects also fit the classification into families. Thus, for the decarboxylation of malonic acid[33] the usual graph displayed the separation of the solvents into one point families with the exception that the picolines seemed to form a three member family. For the Diels-Alder reaction[34] for four solvents listed for the benzoquinone cyclopentadiene addition, carbon tetrachloride and benzene formed a two member family with β_0 of 279°. Ethanol and nitrobenzene separated as expected. For the dimerization of cyclopenta-

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[27] H. M. Papee, W. J. Canady, T. W. Zawidzki, and K. J. Laidler, *Trans. Faraday Soc.*, **55**, 1734 (1959).

[28] L. P. Fernandez and L. G. Hepler, *J. Am. Chem. Soc.*, **81**, 1783 (1959).

[29] L. G. Hepler and W. F. O'Hara, *J. Phys. Chem.*, **65**, 811 (1961).

[30] T. W. Zawidzki, H. M. Papee, W. J. Canady, and K. J. Laidler, *Trans. Faraday Soc.*, **55**, 1738 (1959).

[31] A. I. Biggs, *J. Chem. Soc.*, 2572 (1961).

[32] Biggs came close to anticipating our separation into families in the statement,[31] "It seems therefore that there are $\Delta H^0 - \Delta S^0$ and $\Delta H^0 - \Delta G^0$ relations specific to the substituent group, methyl in one case and nitro or chloro in the other."

[33] Ref. 7, p. 510.

[34] Ref. 7, p. 509.

diene studied by Wasserman[35] the gas phase as well as seven solvents and cyclopentadiene were included. There, cyclopentadiene, carbon disulfide, and the gas phase formed one family with benzene and carbon tetrachloride in a second group about 0.3 kcal. lower in ΔF_0 ($\beta_0 = 255°$ from the two points but would have been 291° if $\Delta\Delta H$ were 0.1 kcal. larger). Acetic acid and ethanol formed a third family about another 0.3 kal. lower ($\beta_0 = 281°$ if $\Delta\Delta H$ had been 0.1 kcal. larger). Nitrobenzene falls about another 0.2 kcal. lower in a class by itself. The solvent "paraffin" fell between the second and third groups although one would have expected it to fall into the first family.

Very striking was the precise data of Berson and co-workers[36] obtained during their work on the effects of solvent on the *endo/exo* ratio for three different Diels-Alder reactions, cyclopentadiene with methyl acrylate (A), with methyl methacrylate (M) and with methyl *trans*-crotonate (C). The graph of the results is shown in Fig. 4 in which $\Delta H_{endo} - \Delta H_{exo}$ or $\Delta\Delta H$ is plotted against $\Delta S_{endo} - \Delta S_{exo}$ or $\Delta\Delta S$. The scatter of points is so great as to discourage an attempt at a general enthalpy-entropy relationship. But by separation of the twelve solvents into four families which fitted a rough graphical slope of 300°: (a) triethylamine, (b) decalin, 1,2-dimethoxyethane, dimethylformamide, pyridine, acetone, and 1,2-dichloroethane, (c) nitromethane and acetonitrile, and (d) methanol, ethanol, and acetic acid, it was possible by the use of least squares and averaging to find $\beta_0 = 291.4°$. The calculated intercepts were for (a) −0.66, 0.02, and 0.69 kcal. for the respective reactions as listed above, (b) −0.80, −0.12, and 0.55 kcal., (c) −0.93, −0.25, and 0.42 kcal., and (d) −1.08, −0.40, and 0.27 kcal. These parameters define the twelve lines shown in Fig. 3 and were used to recalculate $\Delta\Delta H$ from the given $\Delta\Delta S$ values. Comparison of the results showed an average deviation of but ±0.03 kcal., the maximum deviation being only −0.09 kcal. The family criterion applied here was confirmed with satisfying thoroughness despite the tiny range of about 2 kcal. in ΔH and 4 e.u. in ΔS and the subtle effect which was being studied. It should be noted that the decreases in ΔF_0 from one reaction to the next for a given family were the same for each of the families being 0.68 and 0.67 kcal. (one might have used 0.68 for both decreases with little loss in precision) and that the decreases from one family to the next within a given reaction were the same for each of the reactions being 0.14, 0.13, and 0.15 kcal. (again one might have used a constant difference of 0.14 with little loss in precision)! The rationale for the division into families is obscure in that one would have expected decalin to group with triethylamine instead of with the more polarizable family (b). The separation of acetonitrile and nitromethane into a separate group with pronounced alpha-hydrogen activity was no surprise nor was the grouping of acetic acid with methanol and ethanol in view of the common property of oxygen-hydrogen bonds and the ability to form hydrogen bonds. Berson[36] has discussed the relationship between Ω and dielectric constant, Ω being the solvent correlation parameter he has introduced for this series of reactions and solvents. Since Ω was defined to be $\Delta \log k_1$ (the subscript referring to the methyl acrylate reaction) it may be shown for solvents 1 and 2 that his slope b is equal to $[(\Delta\Delta F_{0_2} - \Delta\Delta F_{0_1}) + (\beta_0 - T)(\Delta\Delta S_2 - \Delta\Delta S_1)]/[(\Delta\Delta F_{0_2} - \Delta\Delta F_{0_1})_A + (\beta_0 - T)(\Delta\Delta S_2 - \Delta\Delta S_1)_A]$. Since $(\Delta\Delta F_{0_2} - \Delta\Delta F_{0_1})$ is equal to $(\Delta\Delta F_{0_2} - \Delta\Delta F_{0_1})_A$ as shown by the data, then $(\Delta\Delta S_2 - \Delta\Delta S_1)/(\Delta\Delta S_2 - \Delta\Delta S_1)_A$ must be constant in order for b to remain constant. Since Berson has related his linear free energy equation, $\Delta \log k = a + b\,\Omega$, to several others the same considerations apply to the other linear free energy correlations of solvent data.

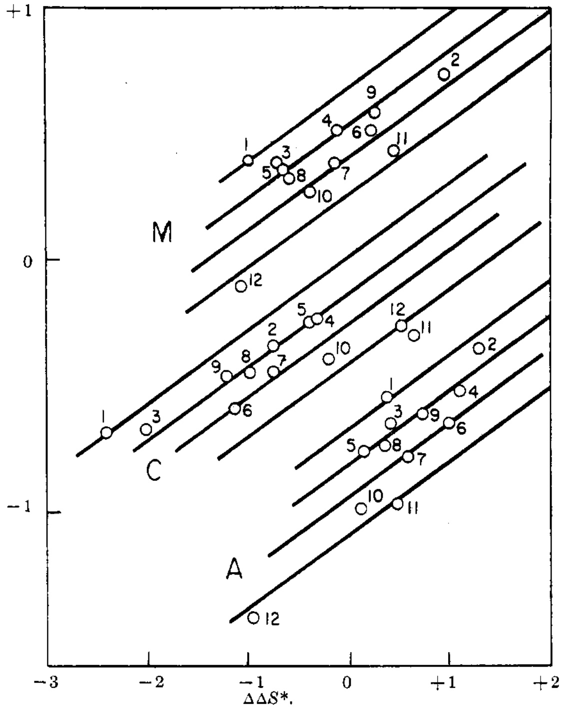

Fig. 4.—Plot of $\Delta\Delta H^*$ against $\Delta\Delta S^*$ for the *endo/exo* ratio for three Diels-Alder reactions,[36] cyclopentadiene with methyl acrylate (A), with methyl methacrylate (M), and with methyl *trans*-crotonate (C) in various solvents; (1) triethylamine, (2) decalin, (3) 1,2-dimethoxyethane, (4) dimethylformamide, (5) pyridine, (6) nitromethane, (7) acetonitrile, (8) acetone, (9) 1,2-dichloroethane, (10) ethanol, (11) acetic acid, and (12) methanol. The lines are drawn with slope $\beta_0 = 291°$.

The solvent effect in the Curtius rearrangement of benzazide[37] showed a similar separation into

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[35] A. Wasserman, *Monatsh.*, **83**, 543 (1952). See also ref. 33.

[36] J. A. Berson, Z. Hamlet, and W. A. Mueller, *J. Am. Chem. Soc.*, **84**, 297 (1962). We are indebted to Professor Berson for the privilege of seeing a preprint.

[37] M. S. Newman, S. H. Lee, Jr., and A. B. Garrett, *ibid.*, **69**, 113 (1947).

families for a little larger list of solvents. A slope of 300° placed heptane and triethylamine in the same family followed by (at roughly 0.3 kcal. decrease in ΔF_0 for each interval) benzene, chlorobenzene, and benzazide in the second family, pyridine, methyl ethyl ketone, ethyl acetate, and dioxane in the third family, and acetic acid, aniline, nitromethane, acetonitrile, and *n*-propyl alcohol in the fourth family. This time the alpha-hydrogen active solvents fell into the same family as the oxygen-hydrogen bond class and the nitrogen-hydrogen containing solvent aniline fell into the same group. Nevertheless, the family characteristics are similar on the whole to the pattern observed by Berson.

The solvent effect on the racemization of various optically active biphenyls[38] tended to give high values of the slopes and some inconsistencies in family membership by various solvents as the optically active substrate was varied. For example, the rate of racemization of 2,2′-dimethoxy-6,6′-dicarboxybiphenyl, (I), was studied in seventeen pure solvents. Despite the scatter, three families could be recognized when ΔH was plotted against ΔS. The lowest family of ten points contained all of the alcohols (except for *tert*-butyl alcohol and dimethylaminoethanol), methanol, ethanol, isopropyl, alcohol benzyl alcohol, trifluoroethanol and glycol, one acid, acetic, and the neutral solvents acetone, dimethylformamide and acetonitrile. The regression line had β_0 = 360°, and ΔF_0 = 30.08 kcal. Recalculation of ΔH from the given ΔS had a maximum deviation of 0.18 kcal., the average deviation was ±0.08 kcal. Lying 0.32 kcal. higher was a second family, tetrahydrofuran, pyridine, dimethoxyethane, and dimethyl sulfoxide. At 0.40 kcal. higher still were dioxane and *tert*-butyl alcohol while dimethylaminoethanol was still higher, about 1 kcal. The dimethyl ester of I was examined in a longer series of solvents (benzyl alcohol, tetrahydrofuran, and dimethylaminoethanol were omitted). The regression line for thirteen solvents (five alcohols, acetic acid, dimethoxyethane, acetone, dimethylformamide, dimethyl sulfoxide, nitrobenzene, cyanobenzene, and propionitrile) had β_0 = 342° and ΔF_0 = 29.80 kcal. Recalculation of ΔH gave a maximum deviation of +0.11 kcal., average deviation of ±0.04 kcal. At 0.28 kcal. higher lay a family of benzene, chlorobenzene, anisole, and acetonitrile with pyridine and trifluoroethanol at an intermediate level. Chloroform, carbon tetrachloride, and dioxane gave an excellent fit to a third line another 0.08 kcal. higher. The diamide of I, seven solvents, gave two families, β_0 = 389°, the lower one with ΔF_0 = 32.74 kcal., average deviation of recalculated ΔH_0 of ±0.03 kcal. had methanol, ethanol, and acetic acid; the higher, ΔF_0 = 33.44 kcal., average deviation of ±0.10 kcal., consisted of acetone, acetonitrile, dimethylformamide, and dimethylsulfoxide. The fourth substrate, *d*-*o*-(2-dimethylaminophenyl)phenyltrimethylammonium *d*-camphorsulfonate, fourteen solvents, gave three families, β_0 = 314°, the lowest with ΔF_0 = 28.14 kcal. had benzyl alcohol, isopropyl alcohol, glycol, glycerol, dimethylformamide, dimethyl sulfoxide, and nitrobenzene, and gave ±0.06 kcal. average deviation upon recalculation of ΔH; the intermediate family, up 0.24 kcal., consisted of methanol, ethanol, acetic acid, and acetonitrile and gave ±0.02 kcal. average deviation; the highest, up another 0.61 kcal., consisted of water, deuterium oxide, and trifluoroethanol and gave ±0.09 kcal. average deviation.

The seven solvents used with the diamide were the only ones used in common for all four substrates (except acetone for the quaternary amine). In general these seven fell into or close to a common family. Dimethyl sulfoxide fell out of the family for I, acetonitrile fell out of the family for the diester although propionitrile was included, while for the diamide and the quaternary amine the family tended to subdivide into a group with active hydrogens and a neutral group. That such a separation might have occurred for a charged species was not too surprising, but the inclusion of the diamide in such a tendency was puzzling. Only for the quaternary amine was the slope within the usual range of 300 ± 30°. No cause may be adduced at this time for high values of the slopes for the other three racemizations.

For solvolysis reactions of a given substrate in a series of pure solvents the data examined showed a separation into one solvent families. Since the solvent must participate in the formation of a product in these cases, perhaps it is not surprising that such a separation should have occurred in comparison with the solvent family effects already discussed. For example, for *t*-butyl chloride[39] ΔH was plotted against ΔS, a slope of 300° applied with a straight edge and the differences in ΔF_0 estimated from one solvent to the next in decreasing order. Ethanol was the highest in ΔF_0 followed by acetic acid at 0.55 kcal. lower, methanol at 0.75 kcal. lower still, dimethylformamide at 2.30 kcal. still lower, formic acid at another 2.00 kcal. lower, and water last with another 2.00 kcal. decrease. Also 90% aqueous dioxane and 90% aqueous acetone fell into the same family with pure ethanol, but this may have been only a coincidence. For *t*-butyl bromide[40] (here and for the subsequent substrates named each solvent named will be followed by the interval in ΔF_0 to the next lower solvent) by the same procedure we found acetic acid, 0.25, ethanol, 1.20, methanol, 4.45, water. Again the point for 90% aqueous dioxane fell on the line through the ethanol point. And as has been

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(38) J. E. Leffler and W. H. Graham, *J. Phys. Chem.*, **63**, 687 (1959); B. M. Graybill and J. E. Leffler, *ibid.*, **63**, 1461 (1959).

(39) S. Winstein and A. H. Fainberg, *J. Am. Chem. Soc.*, **79**, 5937 (1957).

(40) A. H. Fainberg and S. Winstein, *ibid.*, **79**, 1602 (1957).

noted previously for other reactions, the point determined by another investigator, in this case for ethanol as recalculated by Fainberg and Winstein[41] even through ΔH was 0.7 kcal. lower, and ΔS was 2.3 e.u. more negative, fell on the 300° line through the original point. In fact the slope of the calculated line was 304°. For alpha-phenylethyl chloride[42] we found acetic acid, 0.50, ethanol, 1.40, methanol, 4.30, formic acid, 1.55, water. Here the 90% aqueous dioxane was 1.35 kcal. above ethanol. For alpha-phenylethyl bromide[40] the order was acetic acid, 1.70, ethanol, 1.30, methanol, 5.60, water, and aqueous dioxane again was 1.35 above ethanol. For neophyl chloride and bromide[43] only two pure solvents were used, acetic and formic acids, and the intervals were 4.45 and 4.60 for the two substrates. This same interval was 5.05 for *t*-butyl chloride, and 6.20 for alpha-phenylethyl chloride, the only other substrates for which data were available. For the change in substrate from alkyl chloride to alkyl bromide the intervals tended to remain constant but the change RX to R′X produced differences in the intervals. If one considered the solvent held constant while the substrate was changed (acetolyses of all six compounds, formolyses of all but *t*-butyl and alpha-phenylethyl bromides), one found again the separation into one member per family if a slope of 300° was used. The intervals in ΔF_0 were of interest since the shift from *t*-butyl chloride to bromide in acetolysis decreased ΔF_0 by 1.55 kcal., neophyl chloride to bromide in acetolysis, 1.40, in formolysis, 1.55 kcal., but alpha-phenylethyl chloride to bromide in acetolysis only 0.75, exactly one half of the average of the preceding changes. The decrease in ΔF_0 for the changes from neophyl chloride to butyl chloride acetolysis was 5.85 kcal., from neophyl bromide to butyl bromide acetolysis was 6.00 kcal., but from neophyl chloride to alpha-phenyl chloride acetolysis the difference was 5.30 kcal. and for the bromides, 4.70 kcal. The change from the neophyl to butyl appeared to be consistent and constant whether for change in solvent or in substituent but the alpha-phenylethyl was out of line in this respect. That any regularities should have appeared at all from among such diverse moieties as the *primary* but strongly anchimeric neophyl, the *secondary* but benzylic alpha-phenylethyl, and the *tertiary* butyl was surprising.

For the mixed solvents studied by Winstein and Fainberg,[39,40,42,43] each mixture fell into a separate family with little constancy in the ΔF_0 intervals from one composition to the next. Only in mixtures of the relatively closely related solvents, acetic and formic acids, did a close to linear relationship appear for each substrate in going from one solvent to the other.

The acetolyses of tosylates and brosylates reported by Winstein and co-workers[44] did not provide much that was new in family relationships as the substrate was varied since the substrates for the most part represented drastic changes in structure for our purposes. Nevertheless a slope of 300° fitted satisfactorily the two points for *erythro-* and *threo*-3-phenyl-2-butyl tosylates, and for the two points for methylethylcarbinyl, (*s*-butyl), and methyl-*t*-butylcarbinyl brosylates with dimethylcarbinyl about 0.5 kcal. above the line and methylisopropylcarbinyl brosylate about 0.5 kcal. below the line. Cyclohexyl and bornyl tosylates also fitted together.

The solvolysis in 80% aqueous ethanol of a series of 1-methylcycloalkyl chlorides by Brown and Borkowski[45] was more interesting in that the substrate, 1-methylcyclobutyl chloride, fell about 0.6 kcal. above the 300° slope line for *t*-butyl, 1-methylcyclohexyl, and 1-methylcyclotridecyl chlorides. About 2.0 kcal. lower the 1-methylcyclopentyl and 1-methylcycloheptyl points could be envisioned as forming another family with the 1-methyl cyclooöctyl point about another 0.5 kcal. lower. This separation of ring structures was a surprise and indicated an unsuspected effect of ring size on ΔF_0.

Salt effects also fit the scheme as shown by a sampling of the data given by Winstein and co-workers[46] for the effect of added lithium perchlorate on the acetolyses of *trans*-2-*p*-anisylcyclopentyl and *trans*-2-*p*-anisylcyclohexyl bosylates and of cyclohexyl tosylate. Each concentration of added salt set up a single new point in a single new family according to our interpretation, but the three graphically estimated sets of values of $(\Delta F_0)_{\mathrm{LiClO_4}}$, using a slope of 300°, were found to obey the empirical linear relationship, $(\Delta F_0)_{\mathrm{LiClO_4}} = (\Delta F_0)_0 - 3.513\sqrt{M_{\mathrm{LiClO_4}}}$, in which $(\Delta F_0)_0$, the pure solvent value, was equal to 24.59, 27.25, and 27.53 kcal. for the reactions in the order listed above. Calculation of $(\Delta F_0)_{\mathrm{LiClO_4}}$ from this equation for each given concentration of lithium perchlorate used in each of the three reactions, and subsequent use of equation 1 to calculate ΔH from the given values of ΔS in each instance gave values of ΔH within an average deviation of ±0.07 kcal. from the observed values. This was an instance of pushing the enthalpy-entropy relationship to an extreme in that it required the assumption of the slope, but the resulting linear relationship of ΔF_0 with $\sqrt{M_{\mathrm{LiClO_4}}}$ emerged as justification.

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[41] Ref. 39, Note *f* to Table I and their ref. 4 to the work of Ingold, Hughes and collaborators.

[42] A. H. Fainberg and S. Winstein, *J. Am. Chem. Soc.*, **79**, 1597 (1957).

[43] A. H. Fainberg and S. Winstein, *ibid.*, **79**, 1608 (1957).

[44] S. Winstein, B. K. Morse, E. Grunwald, K. C. Schreiber, and J. Corse, *ibid.*, **74**, 1113 (1952); S. Winstein and H. Marshall, *ibid.*, **74**, 1120 (1952); S. Winstein, B. K. Morse, E. Grunwald, H. W. Jones, J. Corse, D. Trifan, and H. Marshall, *ibid.*, **74**, 1127 (1952).

[45] H. C. Brown and M. Borkowski, *ibid.*, **74**, 1894 (1952).

[46] A. H. Fainberg, G. C. Robinson, and S. Winstein, *ibid.*, **78** 2777 (1956); A. H. Fainberg and S. Winstein, *ibid.*, **78**, 2780 (1956).

Discussion

From the sampling of the data in the literature which has been presented it would appear that the Compensation Law is universally applicable if the family restriction is applied properly. Consequently it becomes necessary to continue to study the available data in order to determine if limits exist to the applicability of the Law. At present, β_0 appears to be close to a constant or a multiple thereof and with considerable less certainty the differences in ΔF_0 for different families appear to be constants dependent upon the reaction rate or equilibrium involved. A consideration of the variation in ΔS within a family grouping, fundamental though it may be, is beyond the scope of this paper.

The meaning of β_0 may be approached in several ways. By looking at a diatomic molecule Ruetschi[47] derived an expression equivalent to $E_a\alpha\beta r_e$ as contributing to the entropy of activation. Now the $\alpha\beta r_e$ term, in which α is the linear coefficient of expansion of the bond, β is the coefficient of the difference in interatomic distance in the exponential in the Morse equation in which r_e is the interatomic distance at 0°K, may be assumed to be the reciprocal of $2.3R\beta_0$. If we consider a C—Cl bond with an assumed value of $\beta^{47} = 1.9 \times 10^8$ cm.$^{-1}$ $r_{\text{CCl}} = 1.76 \times 10^{-7}$ cm., and $\beta_0 = 300°$, a solution for α turns out to be 10^{-4} which is rather high in comparison to 10^{-6} observed for diamond as an instance of a substance for which the observed α may properly pertain to the linear expansion of a bond as opposed to the expansion of the van der Waal's distance in the usual crystal of an organic substance. Although the agreement is only approximate, further work on reconciliation should be rewarding. Since bond distances vary through a relatively short range, and if α and β are relatively constant, and if the product should happen to be self-compensating for the small variations in these three factors as Ruetschi has discussed, then β_0 would be relatively constant. Ruetschi puts it that "The basic cause of the Compensation Law appears to be the anharmonic (exponential) character of the potential energy variation with interatomic distance and a relative invariance of this anharmonicity demonstrating itself in a relation between force constant (or frequency) and dissociation energy." So long as the enthalpy-entropy relationship was not separated into the families or groups necessary for β_0 to emerge as relatively invariant, the explanation offered by Ruetschi did not fit the wide fluctuations in the observed slopes of the general enthalpy-entropy relationship. However, uncertainty as to the magnitude of α places limits on this approach to a theoretical evaluation of β_0.

If equation 2 is rewritten as (3), the similarity to

$$\Delta F = \Delta F_0 + \beta_0\Delta S - T\Delta S \qquad (3)$$

the proposal of Taft[48] becomes apparent if ΔF_0 is equated with his "polar activation energy" and $\beta_0\Delta S$ with his 'steric energy of activation.' We may interpret equations 1–3 by the statements that the enthalpy change of a reaction is composed of two terms, the intrinsic enthalpy or polar energy change and the steric energy change which is determined by a constant, β_0, and the entropy change. The constant, β_0, is a measure of the sensitivity of ΔH to ΔS and indicates that the steric energy contribution to the total enthalpy is linear in entropy. The free energy of a reaction is very much less sensitive than is the enthalpy to the entropy since $(\beta_0 - T)$ is small as compared to β_0. Since $(\beta_0 - T)$ decreases and nears zero as T approaches β_0, the free energy draws close to the intrinsic free energy and the members of a family approach each other in rate and equilibrium so that β_0 may be known also as the family isokinetic[2] of iso-free energy temperature.[49] As shown previously, β_0 has been calculated to have values ranging from about 275 to 325° or twice that and we have used 300° as a rough average value. The relation is not very sensitive to the slope since a change of 10° only changes the energy equivalent by 0.01 kcal. per entropy unit.

Since the derivation by Ruetschi implied that β_0 should be independent of temperature, the effect of temperature should be examined since both ΔH and ΔS vary with temperature. First, it is easy to show that for two members of a given family, $\beta_0 = \Delta E_a/2.3\ R\Delta \log A)$, and since both E_a and log A are independent of temperature it follows that β_0 also is temperature independent. The effect of temperature upon the enthalpy-entropy plot may be demonstrated as follows. For the reaction of a given substance at T_1, equation 1 will apply, and we may also write equation 1 for the same reaction at T_2. Subtraction will give equation 4. Now since $\Delta H = E_a - RT$, then $\Delta\Delta H_{\Delta T} = -R\Delta T$,

$$\Delta\Delta H_{\Delta T} = \Delta\Delta F_{0\Delta T} + \beta_0\Delta\Delta S_{\Delta T} \qquad (4)$$

and since it is common practice to calculate ΔS from log A as given in the early part of this paper, $\Delta\Delta S_{\Delta T} = -R\Delta \ln T$. Rearranging equation 4, dropping the subscripts, and making the substitutions gives equations 5 and 6. Now as T_2

$$(\Delta\Delta H/\Delta\Delta S) = (\Delta\Delta F_0/\Delta\Delta S) + \beta_0 \qquad (5)$$

$$(\Delta T/\Delta \ln T) = (\Delta\Delta F_0/R\Delta \ln T) + \beta_0 \qquad (6)$$

approaches T_1, ΔT becomes dT, Δ ln T approaches d ln T, and the ratio ($\Delta T/\Delta$ ln T) approaches T_1

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[47] P. Ruetschi, *Z. physik. Chem.*, **14**, 277 (1958). The β in the Ruetschi expression should not be confused with β_0.

[48] R. W. Taft, Jr., "Steric Effects in Organic Chemistry," M. S. Newman, ed., J. Wiley and Sons, Inc., New York, 1956, pp. 556–675.

[49] It should be noted that the rates or equilibria for members of another family for the same reaction will be determined by the ΔF_0 value for that family when $T = \beta_0$, and it would be a rare coincidence for all families to have the same rates (or ΔF_0) at $T = \beta_0$.

in the limit.[50] If the term in $\Delta\Delta F_0$ on the right in equation 6 is multiplied by $(\Delta T/\Delta T)$, the limits approached, and the substitutions made to give equation 7, it is seen that $R\beta_0$ is the slope of the

$$(\mathrm{d}\Delta F_0/\mathrm{d}T) = -R + (R\beta_0/T) \tag{7}$$

linear plot of $\mathrm{d}\Delta F_0/\mathrm{d}T$ against $1/T$ and $\mathrm{d}\Delta F_0/\mathrm{d}T$ becomes zero at $T = \beta_0$. In other words, for a given substance with a specific location on the ΔH *vs.* ΔS plot for a given temperature, if ΔH and ΔS for the same conditions but calculated for a different temperature are used, the point will be shifted up and to the right along a slope which approaches the original temperature as ΔT approaches zero (if ΔT is not zero, the slope of the line of shift of the point approximates to $\sqrt{T_1T_2}$). Since every point in the same family will shift the same amount in the same direction for the same temperature change used, the new line of points for the family at the new temperature will have the original slope, β_0, but the intercept, ΔF_0, will be changed by an amount equal to $-R(\Delta T - 2.3\beta_0\Delta \log T)$ or $R\Delta T(\beta_0/T - 1)$.

A serious criticism of the Compensation Law has recently been published,[51] in which the authors conclude "that the major part of the observed linear relationship between enthalpy and entropy of activation is very likely the result of experimental error . . . . " This was based on the reasoning that "only if the range of ΔH values exceeds 2δ[51] can any validity be assumed in the observed enthalpy-entropy relationship." They examined eight cases from the literature and found $2\delta \geq$ the observed range of ΔH in each instance. If we understand their contentions, it may be restated in the form that the errors involved in determining ΔH and ΔS are such that a rectangle of dimensions 2δ and 2σ will enclose all of the points of a series of measurements on an enthalpy-entropy diagram and that any regularities observed within the rectangle will probably be the result of nothing but error in the rate measurements. The derivation means something different, in our view—namely, that the uncertainty of a given point lies along a line of slope, $2TT'/(T + T')$ the length of which is specified by 2δ and 2σ, *and only on that line.* In short, the uncertainty of a point is a line, not an area. If a series of points should fall along a line of slope $2TT'/(T + T')$, then the line *may be* nothing more than the error slope, but if the slope should differ from error slope the resulting relation must have validity. Although many of the cases reviewed by us fall in a temperature range such that the temperature term is approximated by 300 ± 20°, still enough exceptions (ref. 26, 35, 36, 37, 38) were found in which $2TT'/(T + T')$ was greater than 300° to lend credence to the reality of β_0 being other than an error slope. The solvent effect on the decomposition of 2,2′-azobis(2-methylpropionitrile) studied by the authors[51] did not allow easy separation into families although the 3 neutral solvents gave $\beta_0 = 341°$, and $2TT'/(T + T') = 343°$. The eight cases they cite from the literature were re-examined. 1. The solvent effect on the decomposition of phenylazotriphenylmethane[52] gave $\beta_0 = 313°$ for a temperature range of 300 to 350°K. 2. The effect of substituents on the decarboxylation of substituted mesitoic acids[53] had only three substituents of which 3-Me and 3-Et gave $\beta_0 = 300°$ for a graphical fit, temperature range 319–359°K. 3,4. Solvent effect on the decarboxylation of picolinic acid[54] utilized thirteen solvents, most of which were disubstituted and difficult to assess for family membership gave a general $\beta = 470°$, temperature range 441–463°K. However, a graphical fit of 300° for β_0 gave additive intercepts which were correct as for 1,4-dimethoxybenzene to 1-bromo-4-methoxybenzene of 0.8 kcal., and from the latter of 1,4-dibromobenzene of 0.7 kcal. 5. The effect of substitution in the benzene ring of phenyldimethylcarbinyl chloride on solvolysis in 90% acetone[55] gave a scatter plot which resolved into families of (a) *m*-COOH, *m*-COOEt, and $(m\text{-}\mathrm{NMe_3})^+$; (b) the same substituents in the *para* position; (c) *m*-CN and *m*-$\mathrm{CF_3}$; and (d) *p*-CN and *p*-$\mathrm{CF_3}$, all different from the parent, graphical slope 300°, temperature range 308–338°K. 6. The effect of substituents on the dehydration of $\mathrm{C_6H_5}$-$\mathrm{CHOHCH_2COCH_3}$ in aqueous acids[56] only had two substituents in the series such that the slope could not be determined. 7. The effect of substituents on the *ortho* Claisen rearrangement[57] had but four substituents of differing families so that β_0 could not be determined. However, a more extensive use of substituents was reported by Goering[58] in a different solvent, diphenyl ether, in which three families of $\beta_0 = 300°$ were easily identified for a temperature range of 458–470°K.! 8. The acid-catalyzed rearrangement of monosubstituted benzhydryl azides[59] had a sufficient number of halogen substituents to show a fit of

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(50) For temperatures in the neighborhood of 300° or larger with ΔT in the range zero to 100°, the ratio becomes equal to $\sqrt{T_1T_2}$ within 0.5%.

(51) R. C. Peterson, J. H. Markgraf, and S. D. Ross, *J. Am. Chem. Soc.*, **83**, 3819 (1961). It should be pointed out that the assumption that ΔH^* and ΔS^* may be calculated from the transition state equation by assigning to them a temperature independent status leads to erroneous results unless the temperature range is small. Their equation 4 is properly for E_a, not ΔH^*, but the derivation of the error term in ΔH^*, δ, happily is correct since the RT term falls out and δ is also the error in E_a. Their equation 10 involving σ, the error in ΔS, simplifies to $\sigma = \delta(T' + T)/(2TT')$ if $1/T'$ is used in place of their $1/T$. Then a plot of ΔH^* *vs.* ΔS^* gives $2TT'/(T' + T)$ as the error slope which approaches T as $T' \rightarrow T$. Note that the ratio also is approximated closely by $\sqrt{TT'}$.[50] Their derivation makes use of only 2 temperatures which, however, may be taken as the extremes of a series of temperatures.

(52) M. J. Alder and J. E. Leffler, *ibid.*, **76**, 1425 (1954).

(53) F. M. Beringer and S. Sands, *ibid.*, **76**, 1425 (1954).

(54) N. H. Cantwell and E. V. Brown, *ibid.*, **75**, 4466 (1953).

(55) Y. Okamoto, T. Inukai, and H. C. Brown, *ibid.*, **80**, 4969 (1958).

(56) D. S. Noyce and W. L. Reed, *ibid.*, **80**, 5539 (1958).

(57) W. N. White, D. Gwynn, R. Schlitt, C. Girard, and W. Fife, *ibid.*, **80**, 3271 (1958).

(58) H. L. Goering and R. R. Jacobson, *ibid.*, **80**, 327 (1958).

(59) C. H. Gudmundsen and W. E. McEwen, *ibid.*, **79**, 329 (1957).

$\beta_0 = 300°$, temperature range 278–318°K. It seems to us that the almost universal occurrence of β_0 as being close to 300° if the separation into families be recognized despite temperature ranges from 273 to 500°K. is evidence that the linear enthalpy-entropy relationship is an established phenomenon despite the validity of the error slope derivation.

If we turn to Hammett's[60] treatment and equate ΔF_0 with his $\Delta E_P + \Delta E_Z$, then $\beta_0 \Delta S$ becomes equivalent to $RT^2[\mathrm{d} \ln (f_E/f_K)][\mathrm{d}T]$ for his discussion of the ketone-enol equilibrium, and $(\beta_0 - T)\Delta S$ becomes equivalent to $-RT \ln (f_E/f_K)$. Elimination of ΔS and solution for $1/\beta_0$ gives $1/\beta_0 = (1/T) + (1/T^2)\ [\ln(f_E/f_K)][\mathrm{d}T/\mathrm{d} \ln (f_E/f_K)]$ which seems to make β_0 a function of T and of (f_E/f_K). Since at temperatures in the neighborhood of 300°, $1/T^2 << 1/T$, only if $[\ln(f_E/f_K)] >> [\mathrm{d}T/\mathrm{d} \ln (f_E/f_K)]$ will $1/\beta_0$ differ appreciably from $1/T$. Another way of looking at the result is that $\beta_0 = T - [RT \ln (f_E/f_K)]/\Delta S$ and again β_0 would not be a constant unless the difference should remain constant, which is not unreasonable.

Turning to a thermodynamic approach, since equations[61] 8 and 9 hold, and since $\beta_0 = (\Delta H - \Delta F_0)/\Delta S$, and by setting ΔH_0 equal to ΔF_0,

$$\Delta H = \Delta H_0 + \Delta a T + (1/2)\Delta b T^2 - \Delta c T^{-1} \qquad (8)$$

$$\Delta S = \Delta a(1 + \ln T) + \Delta b T - (1/2)\Delta c T^{-2} - I \qquad (9)$$

equation 10 is obtained. If T is set equal to β_0, and the terms in Δb and Δc are dropped, (10)

$$\beta_0 = [\Delta a T + (1/2)\Delta b T^2 - \Delta c T^{-1}]/[\Delta a(1 + \ln T) + \Delta b T - (1/2)\Delta c T^{-2} - I] \qquad (10)$$

may be solved for $\ln \beta_0$, (11), in which $\Delta a = \Delta C_P$ so

$$\ln \beta_0 = (I/\Delta a) \qquad (11)$$

that $\ln \beta_0$ becomes equal to the ratio of the integration constant, I, from equation 9 to ΔC_P for a given reaction. Sackur[62] has shown that I for a perfect monatomic gas could be separated into two terms one of which is a constant, C, independent of the nature of the gas and which has been evaluated as 11.074 cal./deg. for translational entropy.[63] Now, if the very doubtful assumption be made that $(I/\Delta C_P)$ is equal to (C/R), then $\beta_0 = 263.1$°K. This result not only links β_0 with the fundamental constants used in the calculation of C but is in rough agreement with our empirical evaluation of β_0 as 300 ± 20°K. Whether β_0 is a true constant or whether it should have values ranging between 280–320°K. or multiples thereof remains obscure. An examination of data for gas phase reactions is indicated in order to broaden the temperature ranges even though the family restriction severely limits the evaluation of β_0 for such instances. In any case the enthalpy-entropy relationship, it is now seen, has not been explored properly because the family relationship was not recognized on the one hand and because the standard state as represented by ΔF_0 was not ever chosen for use in the past since no advantages for such a choice were apparent. Furthermore, all of the linear free energy relationships such as Hammett's equation and Bronsted's catalysis equation are seen to arise as special cases within the Compensation law as revised to include the family relationships and a constant β_0.

The Compensation law needs much more study and inquiry, both theoretical and practical, in order to elucidate the role and relationships for family membership, the magnitude of the entropy changes within a family, the relation of the intrinsic free energies to one another and to other thermodynamic entities, and the relationship of structure to the intrinsic free energies and their differences.

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(60) L. P. Hammett, "Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York, 1940, pp. 73–78.

(61) G. N. Lewis and M. Randall, revised by K. S. Pitzer and L. Brewer, "Thermodynamics," 2nd ed., McGraw-Hill Book Co., Inc., New York, 1961, p. 72, equation 6–18 and p. 165, equation 15–10 for ΔH and ΔF and setting $\Delta S = (\Delta H - \Delta F)/T$.

(62) O. Sackur, *Ann. Physik*, [4], **36**, 958 (1911).

(63) Ref. 61, p. 420.