

method that permits a complex bridge framework to be anchored at more than two sites). Side-bridge locants (primed) are augmented by 32 (max ring size) to indicate the prime.

A phenalene skeleton, substituted by a spiro bridge, complex, and simple side-chains is coded and displayed below as an example that contains all structural types. The main path length is stored as its complement—the number of side-chain carbons. Thus Code 2501 indicates 25 side-chain carbons on C₁₂ main ring. Codes in this column that end in 00 denote acyclic side chains (less complex than cyclic). Code 20802 specifies the most complex side chain (where numbering begins)—the spiro bridge detailed on line 8. Code 20202 points to the [6,10] methano bridge on line 2 that points to the side bridge ('y') on line 3. Code 34 here (32+2) translates to the 2' locant. Code 10604 is for the cyclic side chain (simplified on line 6) at locant 4, etc. Lines with asterisks (**) show more complex or identical configurations (alternate main chains or numberings) that were rejected. Notice the reverse-numbered cyclobutyl group in line 7 and the isopropyl code in column 3 of the last line—indicating a main-chain tie in the substituted butyl side chain. In addition to the reverse-numbered isobutyl group (removed by page editing), line 9 shows the [6,6] initial

numbering of the spiro junction, indicating that the winning search began at C-6. The C-atom positions are read into the starting list line by line. Thus, the first-found ring began at C-12. The program retained C-6 in the starting list as a special case when the others were removed.

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Thermodynamic Implications of Substituent and Solvent Effects on Reactivity

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The theory of the isokinetic relationship and its connection to generalized linear free-energy relationships are outlined, and its practical implications are discussed on the basis of experimentally observed substituent and solvent effects. It is further shown in what way the isokinetic relationship may be applied for detecting changes in reaction pathways within a given series of reaction.

1. INTRODUCTION

Information concerning substituent and solvent effects on chemical reactivity can be correlated in a variety of ways, for example, by means of the Hammett relationship,¹ Brønsted relationships,² or correlations of equilibrium and rate constants with solvent parameters such as donor or acceptor numbers,³ or Reichardt's E_T values.⁴ Such relationships fall into the large class of linear free-energy relationships (LFERs) which is, in a generalized form, the subject of this present paper. Broadly speaking, linear free-energy relationships or LFERs are produced when rate constants or equilibrium constants (or related functions describing kinetic or thermodynamic chemical behavior) of a series of reactions are plotted versus a characteristic quantity measured by means of another reaction series.⁵⁻⁷ Whenever a LFER is found, some quantity must be present that appears in the same functional form in both the "test reaction series" and the "reference reaction series". In what follows this parameter will be given the symbol ξ . As long as only one parameter appears, it may always be expressed in the form of a linear relationship. Furthermore, since thermodynamic functions will be concerned to some extent, the abbreviation x for $1/RT$ will be used, partly to draw attention to the similar meaning of the two parameters. Wherever it is not necessary to distinguish between rate constants and equilibrium constants, both will be referred to as K .

Isokinetic behavior is commonly found⁷ for reaction series in which only one reaction mechanism is followed, and, in fact, this is a necessary condition for the occurrence of an LFER described by not more than one parameter ξ . This produces in turn a common point of intersection of the Arrhenius lines or of the van't Hoff lines ($\ln K$ versus x). This is called the isokinetic relationship (IKR). This effect has also been often referred to as the "compensation effect". However, the latter usually means a proportionality between enthalpic and entropic contributions to K which may occur as an artifact.^{7,8}

Such common points of intersection are also found when the same set of data is depicted for different temperatures in LFER plots. Whereas in the case of the IKR the characteristic intersection abscissa has the dimension of a reciprocal temperature ($x_{\text{iso}} = 1/RT_{\text{iso}}$, where T_{iso} is referred to as the isokinetic temperature), in the latter case a characteristic LFER parameter (ξ_{iso}) is found. In the following, some general properties of these relationships will be explored and then applied to some actual experimental reaction series (involving both substituent and solvent effects) in order to illustrate the practical value of these concepts.

2. THEORY

2.1. Interrelationships between LFERs and IKRs. There are several possibilities open to us for defining the IKR, both in integrated as well as in differential form.⁷ For the present

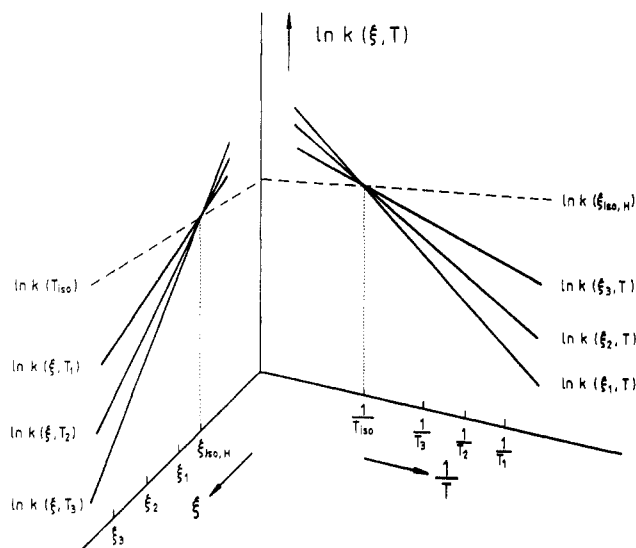


Figure 1. Schematic plot of equilibrium constants (or rate constants) K of a series of three different reactions measured at three different temperatures in the LFER (left-hand side) and the van't Hoff (Arrhenius) plane (right-hand side).

investigations we shall use the latter and define a common point of intersection of van't Hoff or Arrhenius lines via eq 1 and a common point of intersection in an LFER plane via eq 2.

$$\left. \frac{\partial \ln K}{\partial \xi} \right|_{x_{iso}} = 0 \quad (1)$$

$$\left. \frac{\partial \ln K}{\partial \left(\frac{1}{RT} \right)} \right|_{\xi_{iso}} = \left. \frac{\partial \ln K}{\partial x} \right|_{\xi_{iso}} = 0 \quad (2)$$

It has been shown that the ordinates of common points of intersection for representation in different planes must be identical for a given reaction series.^{9,10}

$$\ln K(\xi)|_{x_{iso}} = \ln K(x)|_{\xi_{iso}} \equiv \ln K_{iso} \quad (3)$$

Figure 1 illustrates the relationships occurring in LFER and IKR representations. Using the above conventions, the straight lines in the LFER plane (left-hand side of Figure 1) for different temperatures x_1, x_2, \dots, x_i , are represented by

$$\ln K(\xi, x) = \ln K_u(x) + \xi \partial \ln K(\xi, x) / \partial \xi \quad (4)$$

For example, if one identifies ξ with the Hammett parameter σ the term $\partial \ln K(\xi, x) / \partial \xi$ becomes the Hammett slope ρ . The term $\ln K_u$ refers to a reaction used as a reference for defining $\xi = 0$. For a Hammett reaction series this would be the unsubstituted reactant species.

Using the condition (eq 2) for the common point of intersection in the LFER plane, we get, recalling that $\partial \ln K / \partial x = -\Delta H$ (to be identified with the activation energy $-E_a$ in case of kinetic systems)

$$\xi_{iso, H} = \frac{[\partial \ln K_u(x)] / \partial x}{[\partial \partial \ln K(x)] / [\partial x \partial \xi]} = - \frac{\Delta H_u}{\partial \Delta H(\xi) / \partial \xi} \quad (5)$$

$\xi_{iso, H}$ is therefore the negative reciprocal of the relative change of the reaction enthalpy ΔH with the LFER parameter ξ , using ΔH_u as a reference. (We indicate this by the index H .)

In the van't Hoff or Arrhenius plane the straight lines for different LFER parameters (i.e., different substituents, solvents, etc.) $\xi_1, \xi_2, \dots, \xi_j$ are represented by

$$\ln K(\xi, x) = \ln K_o(\xi) + x \partial \ln K(\xi, x) / \partial x \quad (6)$$

In a more convenient form this can be rewritten following van't Hoff's law (for kinetic systems the Arrhenius laws must

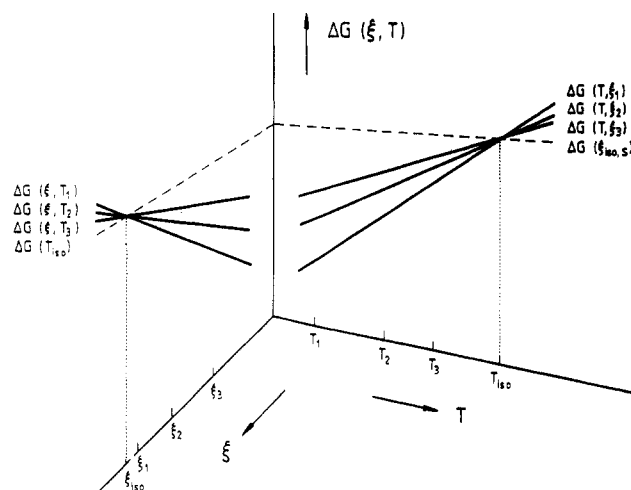


Figure 2. Schematic plot of free energies (or free energies of activation) ΔG of a series of three different reactions measured at three different temperatures in the LFER (left-hand side) and the ΔG versus T plane (right-hand side).

be used yielding the same results with $\ln A$ and E_a replacing ΔS and ΔH) as

$$\ln K(\xi, x) = \Delta S(\xi) - \Delta H(\xi)x \quad (7)$$

which again can be expressed so as to include the IKR

$$\ln K(\xi, x) = \ln K_{iso} - \Delta H(\xi)(x - x_{iso}) \quad (8)$$

where $\Delta S = \ln K_o$ refers to the entropy change and $\Delta H = \partial \ln K / \partial x$ refers to the enthalpy change of the reaction identified with the LFER parameter ξ . $\ln K_{iso}$ is the ordinate position of the common point of intersection in both representations. The IKR condition (eq 1) leads to

$$x_{iso} = \frac{1}{RT_{iso}} = \frac{\partial \Delta S(\xi) / \partial \xi}{R[\partial \Delta H(\xi) / \partial \xi]} = \frac{\partial \Delta S(\xi)}{R \partial \Delta H(\xi)} \quad (9)$$

According to this, x_{iso} represents a proportionality factor between ΔH and ΔS , in agreement with definitions of the compensation effect. However, it should be pointed out that in the case of *actual experimental data* this implication follows from the statistically established existence of an IKR *and not vice versa*.

Data which can be represented in terms of their $\ln K$ values can easily be given in terms of their ΔG representations. Because this gives some further insight into the relationships discussed, LFER and IKR representations in their ΔG form will be derived. Figure 2 gives some details for this.

The left-hand side of Figure 2 includes straight lines represented by

$$\Delta G(\xi, T) = \Delta G_u(T) + \xi \partial \Delta G(\xi, T) / \partial \xi \quad (10)$$

for T_1, T_2, \dots, T_i with a common point of intersection given by

$$\left. \frac{\partial \ln \Delta G}{\partial T} \right|_{\xi_{iso}} = 0 \quad (11)$$

This leads to

$$\xi_{iso, S} = \frac{\partial \Delta G_u(T) / \partial T}{[\partial \partial \Delta G(\xi, T)] / [\partial T \partial \xi]} = - \frac{\partial \Delta S_u}{\partial \Delta S(\xi) / \partial \xi} \quad (12)$$

$\xi_{iso, S}$ is the characteristic abscissa value in this representation and is the reciprocal negative change of the reaction entropy with ΔS_u taken as reference. This value is not identical with the one resulting from the $\ln K$ versus ξ representation, as one is entropy governed and the other is enthalpy related.

The right-hand side of Figure 2 can be represented by

$$\Delta G(\xi, T) = \Delta G_u(\xi) + T \partial \Delta G_c(\xi, T) / \partial T \quad (13)$$

for $\xi_1, \xi_2, \dots, \xi_j$. Again this can be identified with

$$\Delta G(\xi, T) = \Delta H(\xi) + T \Delta S(\xi) \quad (14)$$

Applying the condition for a common point of intersection which is now

$$\left. \frac{\partial \ln \Delta G}{\partial \xi} \right|_{T_{\text{iso}}} = 0 \quad (15)$$

leads to

$$T_{\text{iso}} = \partial \Delta H(\xi) / \partial \Delta S(\xi) \quad (16)$$

which is identical to the result in eq 9. Therefore only one isokinetic temperature T_{iso} is found from both the $\ln K$ and the ΔG representations, whereas two different isokinetic parameters ($\xi_{\text{iso},H}$ and $\xi_{\text{iso},S}$) appear. These two are found to be related via

$$\xi_{\text{iso},H} = \frac{\Delta H_u}{\partial \Delta H(\xi) / \partial \xi} = - \frac{\Delta H_u}{T_{\text{iso}} [\partial \Delta S(\xi) / \partial \xi]} = - \frac{\Delta G_{\text{iso}} + \Delta S_u}{T_{\text{iso}} [\partial \Delta S(\xi) / \partial \xi]} = - \frac{\partial \Delta G_{\text{iso}}}{T_{\text{iso}}} + \xi_{\text{iso},S} \quad (17)$$

2.2. Predictions of Substituent- and Solvent-Dependent Data.

Assume we have an LFER based on a test reaction series (represented by I) measured at temperatures T_I and a reference reaction series (represented by II) measured at temperatures T_{II} . The LFER is then given by

$$\ln \left(\frac{K_I(\xi)}{K_{u,I}(\xi)} \right)_{T_I} = \alpha_{T_I, T_{II}} \ln \left(\frac{K_{II}(\xi)}{K_{u,II}(\xi)} \right)_{T_{II}} \quad (18)$$

namely, straight lines with different slopes for different temperatures. Obviously test and reference reaction series may be taken at different temperatures. (For example, with respect to Hammett's relationship, the ionization constants of benzoic acids, which yield the reference reaction series, are measured at 25 °C, independent of the test reaction series.)

$\alpha_{T_I, T_{II}}$ can be related to a temperature-independent quantity of physical meaning, namely, with

$$\alpha_{T_I, T_{II}} = \alpha_0 \left(\frac{\frac{1}{T_I} - \frac{1}{T_{\text{iso},I}}}{\frac{1}{T_{II}} - \frac{1}{T_{\text{iso},II}}} \right) \quad (19)$$

and

$$\alpha_0 = \frac{\delta \Delta H_I}{\delta \Delta H_{II}} = \frac{\delta \Delta S_I T_{\text{iso},I}}{\delta \Delta S_{II} T_{\text{iso},II}} \quad (20)$$

where $\delta \Delta H$ and $\delta \Delta S$ represent the differences of the enthalpy and entropy of the reaction ξ minus those for the reference reaction ξ_0 (for example, values for the unsubstituted acid when dealing with Hammett LFERs). Knowing this, any $\ln k_{\text{iso}}$ in each one of the representations can be calculated by using

$$\ln \left(\frac{K_{II}(\xi)}{K_{u,II}(\xi)} \right)_{T_{II}} = \frac{\Delta H_u}{\alpha_0} \left(\frac{1}{T_{II}} - \frac{1}{T_{\text{iso},II}} \right) \quad (21)$$

For example, the isosubstituent Hammett parameter σ_{iso} is given, when using $T_{\text{iso}} = -255\text{K}$ for the ionization of the substituted benzoic acids, by

$$\sigma_{\text{iso}} = \Delta H_{0,I} / 2630 \alpha_0 \quad (22)$$

where α_0 is given by eq 23 and represents the temperature-independent slope of a Hammett plot where both coordinates are taken to be in their temperature-dependent form.

$$\alpha_0 = \Delta H_{0,I} / (\Delta H_{0,II} - \Delta H_{\text{iso},II}) \quad (23)$$

2.3. Stochastic Modeling of Chemical Reactions. The above examples visualize the existence of the IKR, for which in the following a short description of the underlying theory will be given.

In this theory,^{7,13} reactant molecules are supposed to become activated through their collision with other molecules of the surrounding medium, which act as a constant-temperature "heat bath". After a random walk over discrete energy levels of the reactants, they reach at the highest point of the barrier a point of no return. The crossing over of this barrier constitutes the chemical reaction rate. This situation can be represented in the form of a Markov process, which, after several advances of the theory, can be rewritten in the form of a Langevin equation where $\sigma(t)$ represents the particle density at a level l , $R(l)$ represents the next-neighbor transition probabilities, $\omega(l)$ is the vibrational frequency associated with the level (l , i.e., for harmonic oscillators $l\omega_0$), and $g(l)$ is a source term "producing" particles to allow for a steady-state solution of the equation:

$$\frac{\partial \sigma(t)}{\partial t} = \frac{\partial}{\partial l} R(l) \left[\frac{\partial \sigma}{\partial l} + \frac{1}{k_B T} \hbar \frac{\partial}{\partial l} \omega(l) \sigma \right] + g(l) \quad (24)$$

A steady-state solution of the master equation (eq 24) has been obtained under the condition of large barriers for a nonequilibrium distribution of reactant molecules among discrete energy levels, with a point of no return at an energy barrier, and connected with a surrounding heat bath:

$$k = \phi(s_N) \left\{ \int_0^{s_N} dl \exp \left(- \frac{\hbar}{RT} \int_0^l \omega(l'') dl'' \right) \int_0^{s_N} dl' \times \frac{\exp \left(\frac{1}{RT} \int_0^{s_N} \omega(l'') dl'' \right)}{P(l')} \phi(l') \right\}^{-1} \quad (25)$$

with

$$\phi(l) = \int_0^l g(l') dl = -R(l) \left[\partial \sigma / \partial l + \frac{\hbar}{RT} \omega(l) \sigma \right] \quad (26)$$

This integral may be solved by partial integration and thereupon yields for the rate constant k of a reaction within the considered reactions series (i.e., with the given reaction profile):

$$k = A_0 (\hbar \omega / kT) P_{s_N, s_{N-1}} \exp(-s_N \hbar \omega / kT) \quad (27)$$

The terms A_0 , $s_N \hbar \omega$, T_{exp} , and $P_{s_N, s_{N-1}}$ represent a constant involving mainly the collision number, the energy barrier height, the temperature of the molecular surroundings of the reactants (i.e., the heat bath), and the quantum-mechanical transition probability of a transition between the reactant level s_{N-1} to the highest reactant level (i.e., the point of no return) s_N , respectively. In condensed phases it must be assumed that the heat bath contains energy stored in the form of vibrational degrees of freedom. This situation is depicted in Figure 3.

The appropriate transition probabilities for a vibrational-vibrational energy transfer are calculated in ref 13 and shown to yield

$$P_{l,m} = l \exp(\omega / \nu) \quad (28)$$

where a resonance condition of the form

$$\nu m = \omega l \quad (29)$$

is included, meaning that energy is exchanged with the highest probability at equal energies. (m represents the number of the heat-bath levels, ν is the associated frequency, and the

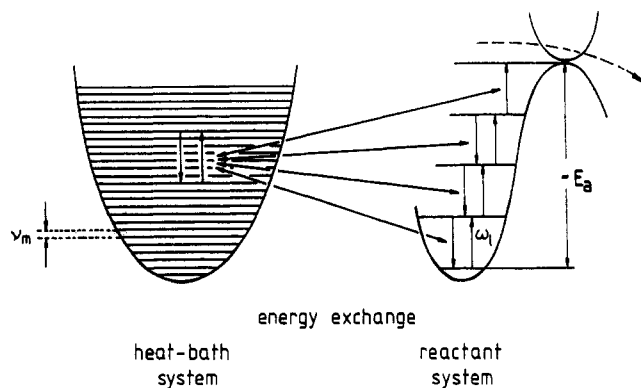


Figure 3. Reactants distributed in a potential well with a point of no return (i.e., a reaction barrier) coupled to a heat bath storing energy in vibrational levels.

resonance condition is given in its form for harmonic oscillators.) Using this, the following form of the rate constant is found (eq 30). In this, ν represents a vibrational heat-bath

$$k = A_0 s_N (h\nu/k_B T_{\text{exp}})^2 \exp[-s_N(\omega/\nu - h\nu/k_B T_{\text{exp}})] \quad (30)$$

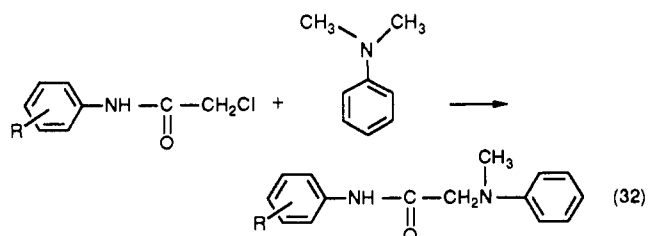
frequency predominantly active in the energy exchange with the reactants. Applying condition 1, the IKR follows naturally when identifying the frequency ω associated with a vibration along the reaction coordinate with ξ (i.e., $[\partial \ln k(\omega)/\partial \omega]_{T_{\text{iso}}} = 0$). Neglecting the term $1/E_a$ as being much smaller than $1/RT$ one obtains

$$1/RT_{\text{iso}} \approx 1/N_L h\nu \quad (31)$$

It should be pointed out at this stage that ξ may also be identified with s_N yielding the same result. This means that, in whatever form the members of the series are represented, they exhibit the same rate at T_{iso} or show a minimum in selectivity at this temperature. It might be significant for this approximation that in the gas phase, where the energy exchange occurs via individual collisions, the experimental results show $1/T_{\text{iso}}$ values near zero, that is, *isoentropic behavior* is observed. At T_{iso} the dependence upon ξ vanishes from the rate equations, and the members of the reaction series cannot therefore be identified by means of their rate constants, i.e., they exhibit *isoselective behavior*. Many examples have been collected to verify this result and are given elsewhere.^{7,8,11,12}

3. APPLICATIONS AND EXPERIMENTAL EXAMPLES

3.1. Isosubstituent Relationships. In Figure 4 the experimental data of the reactions (eq 32) performed in octanol,¹² including a series of different substituents, are depicted in the LFER (left-hand side) and the Arrhenius plane (right-hand side).



First, these results represent an impressive example for the validity of eq 3 as the ordinate positions ($\ln k_{\text{iso}}$) are found to be equal within the experimental errors. Second, this series is an excellent example of how close rate constants of differently substituted reactants can come, as in this case where T_{iso} is almost reached. In fact, reaction series are known¹³ where above this temperature the reverse sequence of in-

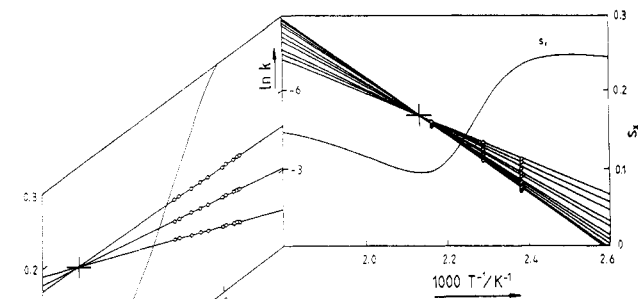


Figure 4. Hammett (left-hand side) and IKR plots (right-hand side) for reaction 32 performed in octanol.¹² The substituents R given in the order of decreasing rate constants within the experimental temperature region are p-NO₂, p-CH₃CO, m-NO₂, m-I, p-Br, H, m-CH₃, p-CH₃, 3,4-(CH₃)₂, and p-CH₃O. The IKR parameters are $\sigma_{\text{iso}} = 2.4$, $\ln K_{\text{iso}} = -6.9$, and $T_{\text{iso}} = 468$ K. The curved lines refer to results from the statistical analysis.⁸ Its minimum gives the position of the common point of intersection.

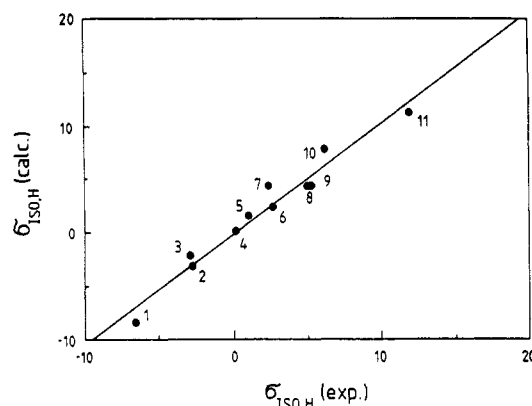


Figure 5. Experimental versus calculated $\sigma_{\text{iso,H}}$ values of Hammett reaction series. 1, alkaline hydrolysis of dinitrophenylbenzoates; 2, decomposition of m-dinitrobenzene complexes; 3, formation of quaternary ammonium salts; 4, ionization ratios of substituted nitroanilines; 5, coupling of phenyldiazonium salts with Brenner acid; 6, formation of anilides of N-phenylsarcosine (see Figure 4); 7, protonation of 3,5-disubstituted anilinium ions; 8, alkaline hydrolysis of ethyl acetate; 9, alkaline hydrolysis of methyl acetate; 10, alkaline hydrolysis of benzyl acetate; 11, esterification of *tert*-butyl perbenzoates.

creasing rate constants in dependence of substituent variation occurs. Third, this reaction series may be taken to exemplify the validity of a theoretical approach⁷ explaining the IKR and evaluating the value of T_{iso} . In this, a necessary condition is a resonant energy exchange of vibrational energy between reactants and their molecular surrounding, i.e., the solvent, which in this case is octanol. The theory requires that for a T_{iso} of 468 K a vibrational frequency of 332 cm⁻¹ must be available in the far-IR spectrum of the solvent. In fact, octanol has such an absorption band with a maximum of 365 cm⁻¹, which is by far broad enough to include the required 332 cm⁻¹. For details see refs 7 and 13.

Figure 5 shows the validity of eq 22 rather impressively for a series of reactions collected in order to examine this relationship. It further shows that the temperature dependence of the Hammett parameters cannot be neglected and is of significant physical meaning. (In fact they originate from the temperature dependence of the ionization constants of benzoic acids.)

3.2. Isosolvent Relationships. A variation of the heat bath itself (i.e., solvent variation) may also yield isokinetic relationships but under the *strong restriction that all the solvents*

of the series have the same vibrational frequency. It is obviously not often the case that for a collection of solvents the necessary frequencies overlap. From this point of view the electroreduction of quinones¹⁴ showing an *isosolvent* relationship is of importance. The reduction potentials of four different quinones have been measured in five different solvents. It was found that the different quinones did not show isokinetic (isequilibrium) behavior: they are obviously different in more than one parameter and do not fall into one series. However a *solvent variation* yielded for each of the quinones highly significant common points of intersection. The isokinetic temperatures are found to be almost the same for the different quinone series and correspond to available IR frequencies of the solvents. The plot for only one of the solvents (namely, that for acetonitrile) does not meet the common point of intersection, and it is significant that this solvent has no absorption frequency in the appropriate region. Similar situations are found for isosolvent relationships for the electroreduction of some solvatochromic nickel(II) and copper(II) complexes, imine–enamine tautomerism, chlorine isotopic exchange reaction, and olefine cycloaddition as discussed in some detail in refs 10 and 13.

All these observations of IR absorption bands being linked in some way to T_{iso} through an IKR may be taken as a hint that a resonance condition determines the “chosen” IR frequency corresponding to an isokinetic relationship. The fact that in the study of the electroreduction of quinones in various solvents (above) the reactants themselves exhibit IR absorption at these frequencies might reinforce this conclusion.

4. CHANGES IN REACTION MECHANISM

From the occurrence of a distinct IKR, it can generally be concluded that only one reaction mechanism is present for all reactions included in this series. In the case where some Arrhenius or van't Hoff lines of the considered reaction series miss the condition of the IKR, or in the case where two or more common points of intersection are found, either a change in the reaction mechanism occurs within the series or the resonance condition between reactants and their molecular surroundings is not fulfilled. In the case of a substituent variation of the reactants with the reaction performed in one solvent (or on one solid-state catalyst), the former must be the case.^{5,7,9}

The theoretical description given above concludes that no general changes in the reaction profile (for example, by including a new minimum or maximum according to an intermediate or a new barrier) within one IKR reaction series may occur. Obviously when this is the case the IKR condition is not fulfilled and more than one common point of intersection may occur. The connections between LFERs discussed above include a similar argument. One IKR can only be found when *only one parameter* is changed within the reaction series. In case of a change of the reaction mechanism additional to the parameter describing substituent or solvent variation, another “information” becomes necessary so that the required condition is not fulfilled.

In fact, the IKR analysis has brought to light several, sometimes unexpected, examples of a change in mechanism. Some examples follow:

One example is given by the partitioning of pyridylalkylamides in octanol/water and di-*n*-butyl ether/water systems.^{15,16} The partition coefficients of a series of 12 isomeric and homologous pyridylalkylamides split, rather surprisingly perhaps, into two groups when analyzed for an IKR. One group consists of o-C₁, o-C₂, o-C₃, o-C₄, m-C₁, m-C₃, m-C₄, and p-C₄; the other includes m-C₃, m-C₄, p-C₁, p-C₂, and p-C₃, where o-, m-, and p- refer to ortho-, para-, and meta-substituted compounds with 1, 2, 3, or 4 CH₂ groups of the alkyl rest.

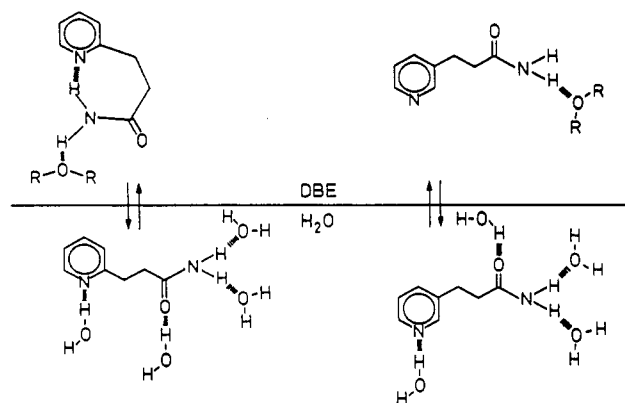


Figure 6. Structural changes of pyridylalkylamides in dibutyl ether/water systems. The left-hand side includes o-C₁, o-C₂, o-C₃, o-C₄, m-C₁, m-C₃, m-C₄, and p-C₄ species; the right-hand side includes m-C₃, m-C₄, p-C₁, p-C₂, and p-C₃, with o-, m-, and p- equal to ortho-, para-, and meta-substituted compounds with 1, 2, 3, or 4 CH₂ groups of the alkyl rest, respectively.

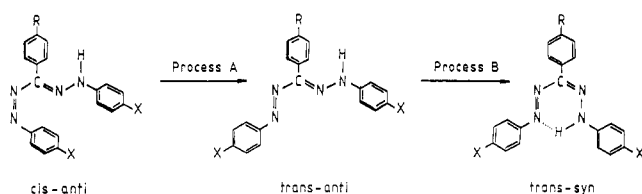
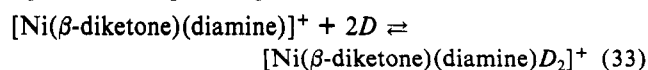


Figure 7. Chemical pathway of the isomerization of substituted formazanes in a two-step reaction after excitation by radiation of the trans-syn species to the cis-anti species.

The splitting into the two groups lead us to realize that the former group is able to form intramolecular N...H–N bonds while the latter, on steric grounds, is not (see Figure 6). Although this result is confirmed without simple geometrical experimental results, it would hardly have been found without following the hint arising from the occurrence of two IKRs.

Another example is given by the isomerization of formazanes where for each of the reaction steps depicted in Figure 7 two IKRs are found.^{7,13} According to this two pathways occur, namely, a rotational and an inversion mechanism. The former occurs in the case of electron-withdrawing substituents where the N=N bond (process A) or the C=N bond (process B) is weakened to allow for a rotation. Electron-pushing substituents lead to a strengthening of these bonds, so only an inversion mechanism is allowed. This example is of particular importance because they originally found only one straight line on the basis of a ΔH versus ΔS plot and argued that—contrary to their chemical expectations—only one reaction mechanism is present in this series. A statistically sound IKR analysis later clearly demonstrated the existence of *two* intersection points for this series of reactions. In other words, two mechanisms are indeed present—in agreement with chemical intuition!

As a further example, giving evidence for the applicability of the method for equilibrium systems, square planar Ni(II) complexes, with a diamine plus a β -diketone as ligands, known to show solvatochromism and thermochromism due to the equilibrium (eq 33) is presented.



The influence of the solvent molecules *D* which are acting as Lewis bases (i.e., as electron-pair donor molecules) and of different substituents on either of the ligands have been investigated in detail,¹⁷ yielding thermodynamic and structural results on solvent and substituent effects for the transformation of square planar Ni(II) complexes with a diamine and a β -diketone as ligands into octahedrally coordinated species by

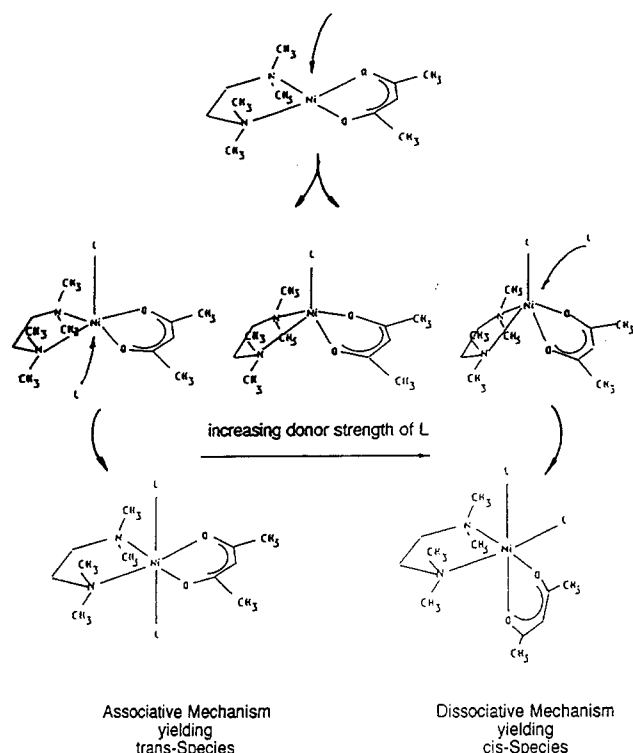


Figure 8. Reaction pathway of the formation of five- and six-coordinated mixed ligand Ni(II) complexes.

addition of donor ligands (mainly donor solvent molecules). Not unexpectedly a five-coordinated species appears to be involved in the equilibrium. The charge redistribution depends upon the donor strength of the solvent donor molecule *D* and leads, in the case of the less symmetric five-coordinated species, to considerable changes of the bond angles (see Figure 8).

Analysis of the temperature-dependent equilibrium constants revealed two isokinetic groups, namely, one for weaker donor solvents such as acetonitrile, acetone, alcohols, etc., and another one including stronger donor solvents like formamide, *N,N*-dimethylformamide, pyridine, dimethyl sulfoxide, etc. According to the bond angle variation rules, strong donor solvents lead to strong distortion of the planar arrangement of the β -diketonate and the diamine in the case of the five-coordinated species. At the same time, the bond length variations lead to a weakening of the Ni–O bonds at the β -diketonate. Thus, in strong donor molecules one Ni–O bond is broken, the β -diketonate rotates, and a cis configuration results. In weak donor solvents these changes are less pronounced so that the β -diketonate remains in nearly the same position within the molecule and the second donor molecule is simply added to form the trans isomer. The former reaction path may be described in terms of a dissociative mechanism whereas the latter may be described in terms of an associative mechanism (see Figure 8). In fact X-ray analysis of the solid-state octahedral complexes reveals unambiguously the occurrence of the cis and trans species.¹⁸

It is interesting that for the CF_3 -substituted species only one common point of intersection is found, pointing to the occurrence of only one IKR associated with only one reaction mechanism. However, for these species the equilibrium con-

stants for both the formation of the five- and the six-coordinated species are, even for the weak donor molecules, much higher than those of the unsubstituted species with strong donor molecules. Therefore, it must be assumed that in this case for all donor solvents the reaction runs via the dissociative mechanism leading to the cis species.

In conclusion, it may be pointed out that the occurrence of an IKR yields to information about the behavior of a series of reactions: The abscissa position of the associated point of intersection of the van't Hoff or Arrhenius lines refers to the energy exchange between reactants and the surrounding molecular heat bath, and one might shed light on the "physics" of the interaction. The ordinate position of the common point of intersection reflects the "chemistry" (i.e., the potential profile) of the system visualizing the reactivity as well as the reaction pathway or changes of this within the considered reaction series in case of more than one IKR.

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