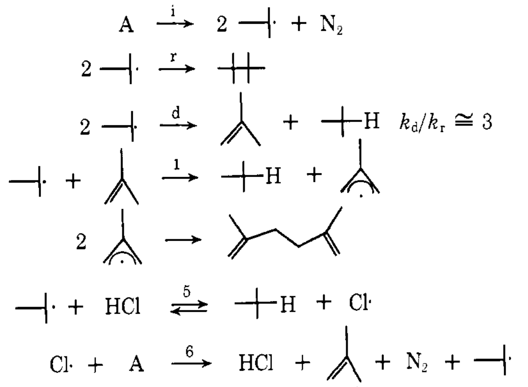
Appendix B

Steady-State Analysis of HCl Accelerated 2,2′-Azoisobutane Pyrolysis. The mechanism change from that invoked in Appendix A is changed only by the addition of reactions 5 and 6.



Since, in early stages of reaction, the rate of reaction 6 will be simply equal to the rate of reaction 5

$$\frac{d(i\text{-}C_4H_8)}{dt} = 0 = k_d(t\text{-Bu}\cdot)^2 + k_5(t\text{-Bu}\cdot)(\text{HCl}) - {}^1/_2k_1(t\text{-Bu}\cdot)(i\text{-}C_4H_8)$$

$$(i\text{-}C_4H_8)_{ss} = \frac{2k_d(t\text{-Bu}\cdot) + 2k_5(\text{HCl})}{k_1} \qquad (1)$$

$$\frac{d(t\text{-Bu}\cdot)}{dt} = 2k_i(\text{A}) - 2(k_r + k_d)\,(t\text{-Bu}\cdot)^2 - k_1(t\text{-Bu}\cdot)(i\text{-}C_4H_8)$$

$$(t\text{-Bu}\cdot)_{ss} = \left[\frac{2k_i(\text{A})}{2(k_r + k_d) + k_1\dfrac{(i\text{-}C_4H_8)}{(t\text{-Bu}\cdot)}}\right]^{1/2} \qquad (2)$$

Substituting (1) in (2)

$$(t\text{-Bu}\cdot)_{ss} = \left[\frac{2k_i(\text{A})}{2(k_r + k_d) + \dfrac{2k_i[k_d(t\text{-Bu}\cdot) + k_5(\text{HCl})]}{(t\text{-Bu}\cdot)k_1}}\right]^{1/2}$$

$$(t\text{-Bu}\cdot)_{ss} = \left[\frac{k_i(\text{A})}{k_r + 2k_d + \dfrac{k_5(\text{HCl})}{(t\text{-Bu}\cdot)}}\right]^{1/2}$$

$$(t\text{-Bu}\cdot)_{ss}{}^2(7k_r) + k_5(\text{HCl})(t\text{-Bu}\cdot) - k_i(\text{A}) = 0$$

$$(t\text{-Bu}\cdot)_{ss} = \frac{-k_5(\text{HCl}) \pm [k_5{}^2(\text{HCl})^2 + 28k_rk_i(\text{A})]^{1/2}}{14k_r}$$

Since the acceleration corresponds to the rate of reaction 5, the total rate of azobutane decomposition will be given by

$$\left(-\frac{d(\text{A})}{dt}\right)_{\text{HCl}} = k_i(\text{A}) + k_5(\text{HCl})(t\text{-Bu}\cdot)$$

$$\left(-\frac{d(\text{A})}{dt}\right)_{\text{HCl}} = k_i(\text{A}) + k_5(\text{HCl})\left[\frac{[k_5{}^2(\text{HCl})^2 + 28k_rk_i(\text{A})]^{1/2} - k_5(\text{HCl})}{14k_r}\right]$$

Rate–Equilibria Relationships and Proton-Transfer Reactions

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Abstract: In view of the central role that Hammond's postulate has played in the attempt to correlate structural variations and chemical reactivity, it would be desirable to extend this concept beyond its qualitative nature. This has now been accomplished. From a derivation based on Hammond's postulate, equations are obtained that relate the free-energy barrier of a reaction to ΔF and the barrier height at $\Delta F = 0$ ($\Delta F_0{}^*$). The final equations are identical with those originally developed by Marcus for electron-transfer reactions. Using these results, rate constants (k_b and k_{-b}) are calculated for the forward and reverse directions of a simple one-step proton-transfer reaction, where $\alpha = d \log k_b/d \log (k_b/k_{-b})$. The rate constants k_b and k_{-b} are incorporated into a multistep mechanism for proton transfer, and the "observed" rate constants k_{for} and k_{rev} are calculated. The "experimental" Brønsted coefficient, $\alpha_{exp} = d \log k_{for}/d \log (k_{for}/k_{rev})$, is computed. A comparison of α and α_{exp} allows a test of the frequently invoked assumption that an experimental Brønsted coefficient is a true indicator of transition state structure. Results are obtained which show that even when Hammond's postulate is obeyed, α_{exp} is not always reliable for predicting the position of the transition state along the reaction coordinate.

The Brønsted equation has been applied to a wide variety of reactions including general acid and general base catalysis,[2a] nucleophilic catalysis,[2b] and proton exchange reactions. These latter reactions have involved not only oxygen, nitrogen, and sulfur acids[3] but also carbon acids, including nitroalkanes,[4] cyanocarbons,[5] ketones,[6] sulfones,[7] and hydrocarbons.[8]

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[1] National Institutes of Health Predoctoral Fellow, 1969–1972.

[2] (a) R. P. Bell, "The Proton in Chemistry," Cornell University Press, Ithaca, N. Y., 1959, Chapter X; (b) T. C. Bruice and S. J. Benkovic, "Bio-organic Mechanisms," Vol. I, W. A. Benjamin, New York, N. Y., 1966.

[3] M. Eigen, *Angew. Chem., Int. Ed. Engl.*, **3**, 1 (1964).

[4] (a) R. G. Pearson and R. L. Dillon, *J. Amer. Chem. Soc.*, **72**, 3574 (1950); (b) R. P. Bell and D. M. Goodall, *Proc. Roy. Soc., Ser. A*, **294**, 273 (1966); (c) M. J. Gregory and T. C. Bruice, *J. Amer. Chem. Soc.*, **89**, 2327 (1967).

[5] K. F. Bonhoeffer, K. H. Geib, and O. Reitz, *J. Chem. Phys.*, **7**, 664 (1939).

The Brønsted equation has been one attempt to correlate the rate of a reaction with the free-energy difference between products and reactants. Rate–equilibria relationships have a certain mesmerizing quality, since there have been a vast number of attempts to find such correlations despite the fact that it has long been recognized that there is no necessary relationship between rates and equilibria. The rate–equilibrium concept encompasses an important qualitative idea of chemistry, and it is of paramount importance to recognize its scope and limitations. The purpose of the present discussion is to develop a mathematical model for a rate–equilibrium relationship and use it to demonstrate a potential trap for those who would apply such relationships in the hope of extracting information concerning properties of the transition state.

For a long time it was believed that Brønsted coefficients for proton abstractions fall in the range of 0–1.[3,9] Furthermore, α_{exp} was interpreted as being the degree to which the transition state resembles the products of a reaction.[9] Coupled with the notion that during a chemical reaction structural changes and substituent interactions occur continuously from the initial state to the final state, this concept of α_{exp} was used to glean fine mechanistic detail about transition state structure and reaction mechanism.[9] Recently, however, Bordwell, *et al.*,[10] have shown that the base-catalyzed proton abstraction of certain nitroalkanes gives a Brønsted coefficient greater than 1. This finding poses serious theoretical problems since the usual meaning assigned to α cannot be applied unless $0 \leq \alpha \leq 1$. Although several explanations[10–13] of this phenomenon have been offered, the significance of the Brønsted slope might still be questioned, and one is forced to reexamine the meaning of a "normal" Brønsted coefficient between 0 and 1.

Proton-transfer reactions have often been represented as proceeding through a one-step mechanism. The previous treatments of deviant Brønsted relationships have focused attention on this single step,[10–13] involving the transfer of a proton from an acid to a base.

$$\text{A—H} + \text{B}^- \rightleftarrows \text{A}^- + \text{B—H}$$

However, a one-step mechanism is often inadequate. A common example is the isotopic exchange of weak carbon acids.

$$\text{B}^- + \text{D—R} \underset{k_{-\text{b}}}{\overset{k_\text{b}}{\rightleftarrows}} \text{B—D} + \text{R}^- \underset{k_\text{c}}{\overset{\text{BH}}{\longrightarrow}} \text{R—H} + \text{B}^-$$

When the intermediate carbanion is sufficiently reactive, recapture of deuterium from B–D by R⁻ (internal return) may be faster than diffusion of B–D into the solvent pool.[14] From a steady state treatment it can be shown that $k_{\text{obsd}} = k_\text{b}k_\text{c}/(k_{-\text{b}} + k_\text{c})$. Unless $k_{-\text{b}} \ll k_\text{c}$, the observed rate constant for exchange will not equal the rate constant for ionization, k_b. As the carbon acid becomes less acidic, $k_{-\text{b}}$ will increase, and k_{obsd} will no longer be a measure of the rate of ionization. Any relationship between $\log k_{\text{obsd}}$ and $-\text{p}K_\text{a}$ will be obscured by the importance of solvent diffusion as a component of the rate-determining step.

In aqueous solutions the situation is even more complex. Eigen[3] has investigated the proton transfers between a variety of acceptors and donors including acetic acid, phenol, thioglycol, imidazole, aniline, and ammonia. The Brønsted plots for these reactions show the expected transition of α_{exp} from 0 to 1. When the donor (A–H) is a much stronger acid than the conjugate acid of the base (B–H), the proton-transfer rate is independent of $\Delta\text{p}K$ ($\Delta\text{p}K = \text{p}K_{\text{B–H}} - \text{p}K_{\text{A–H}}$) and depends only on the rate at which the reactants diffuse together to form an "encounter" complex, which for oxygen and nitrogen acids is a hydrogen-bonded species; the Brønsted slope is 0. When the conjugate acid of the acceptor (B–H) is a much stronger acid than the donor (A–H), the reverse reaction is encounter controlled, and α_{exp} equals 1. In the intermediate region neither reaction is encounter controlled, the proton-transfer step is rate limiting, and α_{exp} is between 0 and 1. This is illustrated in Figure 1. Eigen has proposed the following mechanism to account for this behavior.

$$\text{A—H} + \text{B}^- \underset{k_{-\text{a}}}{\overset{k_\text{a}}{\rightleftarrows}} (\text{A—H}\cdots\text{B})^- \underset{k_{-\text{b}}}{\overset{k_\text{b}}{\rightleftarrows}}$$

$$(\text{A}\cdots\text{H—B})^- \underset{k_{-\text{c}}}{\overset{k_\text{c}}{\rightleftarrows}} \text{A}^- + \text{H—B}$$

The observed rate constant for a reaction proceeding through Eigen's mechanism is given by the following expression[3]

$$k_{\text{obsd}} = k_\text{a}k_\text{b}k_\text{c}/(k_{-\text{a}}(k_{-\text{b}} + k_\text{c}) + k_\text{b}k_\text{c}) \qquad (1)$$

Under certain conditions this expression simplifies to three limiting cases. (1) $k_{\text{obsd}} = k_\text{a}$; $k_\text{b} \gg k_{-\text{a}}$, $k_\text{c} \gg k_{-\text{b}}$. Formation of the encounter complex from the reactants is rate limiting. (2) $k_{\text{obsd}} = (k_\text{a}/k_{-\text{a}})k_\text{b}$; $k_{-\text{a}} \gg k_\text{b}$, $k_\text{c} \gg k_{-\text{b}}$. Proton transfer is rate limiting. (3) $k_{\text{obsd}} = (k_\text{a}/k_{-\text{a}})(k_\text{b}/k_{-\text{b}})k_\text{c}$; $k_{-\text{a}} \gg k_\text{b}$, $k_{-\text{b}} \gg k_\text{c}$. Breakdown of the encounter complex to products is rate limiting.

Eigen[3] has demonstrated that the rate of encounter complex formation for most oxygen and nitrogen acids is in the range 10^9–10^{11} M^{-1} sec^{-1}, which is consistent with that expected for a diffusion-controlled encounter. However, for compounds where hydrogen bond formation is difficult, the rate of encounter complex formation is no longer diffusion controlled.[3] This seems to be the case for certain bases reacting with acetylacetone and related carbon acids and to a certain extent for thiols and protonated phosphines.[3] The effect is also observed with oxygen and nitrogen acids if intramolecular hydrogen bonding is important.[3] These observa-

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(6) (a) R. P. Bell, *Trans. Faraday Soc.*, **39**, 253 (1943); (b) R. P. Bell and J. E. Crooks, *Proc. Roy. Soc., Ser. A*, **286**, 285 (1965).

(7) (a) J. Hochberg and K. F. Bonhoeffer, *Z. Phys. Chem., Abt. A*, **184**, 419 (1939); (b) G. Schwarzenbach and E. Felder, *Helv. Chim. Acta*, **27**, 1701 (1944).

(8) (a) A. Streitwieser, Jr., and J. E. Hammons, *Progr. Phys. Org. Chem.*, **3**, 41 (1965); (b) D. J. Cram, "Fundamentals of Carbanion Chemistry," Academic Press, New York, N. Y., 1965.

(9) J. E. Leffler and E. Grunwald, "Rates and Equilibria in Organic Reactions," Wiley, New York, N. Y., 1963.

(10) (a) F. G. Bordwell, W. J. Boyle, Jr., J. A. Hautala, and K. C. Yee, *J. Amer. Chem. Soc.*, **91**, 4002 (1969); (b) F. G. Bordwell, W. A. Boyle, Jr., and K. C. Yee, *ibid.*, **92**, 5926 (1970).

(11) (a) A. J. Kresge, *ibid.*, **92**, 3210 (1970); (b) A. J. Kresge, H. L. Chen, Y. Chiang, E. Murrill, M. A. Payne, and D. S. Sagatys, *ibid.*, **93**, 413 (1971).

(12) R. A. Marcus, *ibid.*, **91**, 7224 (1969).

(13) P. C. Mowery and A. Streitwieser, Jr., "Ions and Ion Pairs in Organic Chemistry," M. Swarc, Ed., Wiley-Interscience, New York, N. Y., in press.

(14) (a) D. J. Cram, D. A. Scott, and W. D. Nielsen, *J. Amer. Chem. Soc.*, **83**, 3696 (1961); (b) A. Streitwieser, Jr., W. C. Langworthy, and D. E. Van Sickle, *ibid.*, **84**, 251 (1962); (c) J. E. Hofmann, A. Schriesheim, and R. E. Nickols, *Tetrahedron Lett.*, **22**, 1745 (1965).

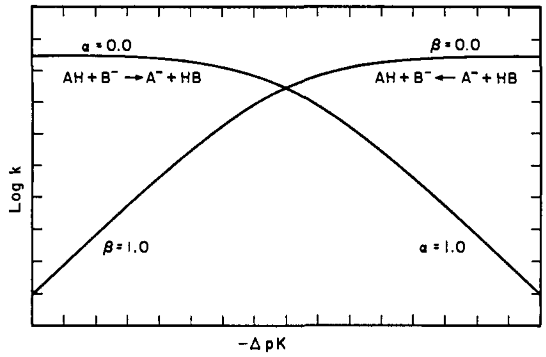

Figure 1. Brønsted plot, forward and reverse reactions.

tions suggest that encounter complex formation is not necessarily simple diffusion together of the reactants and that a barrier, in addition to that required for diffusion, exists toward breaking internal hydrogen bonds or replacing solvent around the base with a substrate molecule that forms a weak hydrogen bond. The use of encounter complexes in the kinetic mechanism implies that such solvational changes occur separately from the actual proton transfer step (which may include further solvent reorganization) as distinguished from a one-step reaction where all solvational changes and the proton transfer must occur simultaneously. Eigen's work shows that in aqueous solution the proton-transfer step can be separated from diffusion of the reactants and reorientation of the solvent to allow contact between the proton and the base prior to proton transfer.[3] The importance of internal return[15–17a] for proton-exchange reactions of certain hydrocarbons suggests that this conclusion may be extended to the proton-transfer reactions of carbon acids in organic solvents. When internal return is high ($k_c \ll k_{-b}$), diffusion into the solvent (k_c) is rate limiting in the forward direction, and this requires that the rate-limiting step for the reverse reaction be the encounter between the carbanion and protonated base (k_{-c}), rather than the transfer of the proton to the carbanion (k_{-b}). Internal return demands that encounter of the carbanion with the conjugate acid of the base be kinetically distinct from the proton-transfer step. If the encounter of the carbon acid with the base is also separable from proton transfer, then it could be concluded that the hydrogen-bonded encounter complexes of aqueous proton transfers have their counterparts in the hydrogen exchange reactions of carbon acids. This idea has also been entertained by Ritchie and Uschold,[17a] who have used Eigen's mechanism to rationalize certain features of the Brønsted relationship for weak acids in DMSO and methanol.

In a general sense, the term "encounter complex" means only that processes associated with the transport and orientation of the reactants are kinetically distinguishable from the actual reaction step. *One of the purposes of this paper is to demonstrate that when such a distinction is possible, it is highly important to apply rate-equilibrium relationships only to the reaction step and not to the overall process.*[17b,c] At first glance it might seem sufficient to argue that α_{exp} is a function of only k_b and k_{-b} except at the extreme limits of diffusion control. However, it will be shown that the effects of the encounter steps on α_{exp} can often be significant even when the rate-determining step is proton transfer.

One important concern (*vide infra*) is the relationship between the experimental α ($\alpha_{\mathrm{exp}} = \mathrm{d}\log k_{\mathrm{for}}/\mathrm{d}\log(k_{\mathrm{for}}/k_{\mathrm{rev}})$) and the "true" value of α ($\alpha = \mathrm{d}\log k_b/\mathrm{d}\log k_b/k_{-b}$). The concept of "true value of α" must be taken with reservation, since it is debatable whether or not transition state structure varies in any predictable manner according to free-energy differences between reactants and products. Nonetheless, this has remained a popular idea, and one of the most frequently invoked variations has been Hammond's postulate.[1]

Hammond's postulate can be stated in the following way: if two states occur consecutively during a reaction process and have nearly the same energy content, their interconversion will involve only a small reorganization of molecular structure.[18] Hammond's postulate interpreted literally means that extremely exothermic reactions with small activation energies will have transition states that closely resemble the reactants, whereas the transition states of strongly endothermic reactions with large activation energies will bear a close resemblance to products. Strictly interpreted, Hammond's postulate applies only to the two extremes of highly exothermic and highly endothermic reactions. Nevertheless, one often sees the statement that the geometry of the transition state bears a closer structural resemblance to the less stable side of the reaction coordinate.[4b] This latter idea was put in more quantitative form by Leffler[9,19] who suggested that since a transition state has considerable resemblance to the reactants and products both in composition and structure, it is reasonable to suppose that changes in its free energy might be represented as a linear combination of the corresponding changes in the free energies of the reactants and products.

$$\delta F^* = \alpha\delta F_p + (1 - \alpha)\delta F_r \qquad (2)$$

Note that as $\delta F^* \to 0$, this expression reduces to $\alpha = \mathrm{d}\Delta F^*/\mathrm{d}\Delta F$, which is simply a restatement of the definition of α given above. According to Hammond's postulate, a transition state for a highly endothermic reaction will have a structure similar to the products. If the products are stabilized by a small change in structure, it follows that the transition state should be stabilized to the same extent. This is the concept embodied by Leffler's equation except that it applies to the entire distance of the reaction coordinate. Consequently, Leffler's proposal might be regarded as an extended version of Hammond's postulate. Accordingly, eq 2 and eq 7 and 8, which are derived subsequently, will be referred to as the "extended Hammond's postulate" (*i.e.*, EHP). This idea is illustrated in Figure 2. When F_p and F_r are equal, α is 0.5. If the products are stabilized by a small increment, $\mathrm{d}F$, then the transition state will be stabilized by $\alpha\mathrm{d}F$, or $^1/_2\mathrm{d}F$. As the transition state becomes more reactant-like, α will decrease by a small amount to α'. Sta-

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(15) A. Streitwieser, Jr., W. B. Hollyhead, G. Sonnichsen, A. H. Pudjaatmaka, C. J. Chang, and T. L. Kruger, *J. Amer. Chem. Soc.*, **93**, 5096 (1971).

(16) J. Almy, D. C. Garwood, and D. J. Cram, *ibid.*, **92**, 4321 (1970), and previous papers.

(17) (a) C. S. Ritchie and R. E. Uschold, *ibid.*, **90**, 3415 (1968). See the following papers for alternative treatments of diffusion steps: (b) R. A. Marcus, *Discuss. Faraday Soc.*, **29**, 129 (1960); (c) J. Halpern, R. J. Legare, and R. Lumry, *J. Amer. Chem. Soc.*, **85**, 680 (1963).

(18) G. S. Hammond, *ibid.*, **77**, 334 (1955).

(19) J. E. Leffler, *Science*, **117**, 340 (1953).

bilizing the products by another increment, dF, will stabilize the transition state by α'dF. If this process is continued indefinitely, α will approach 0, and the transition state will eventually become completely reactant-like. Further stabilization of the products causes no change in transition state stabilization. Qualitatively, it can be seen that the higher the barrier when $\Delta F = 0$ (ΔF_0*), the larger $\Delta F_{\max}$ ($\Delta F_{\max} = F_p - F_r$ when $\Delta F^* = 0$) will be. Since $\alpha = 0$ at $-|\Delta F_{\max}|$ and $\alpha = 1$ at $+|\Delta F_{\max}|$, it is clear that α must be some function of ΔF. Furthermore, this function should be continuous and single valued (*i.e.*, only one value of α for each ΔF, $-|\Delta F_{\max}| \leq \Delta F \leq |\Delta F_{\max}|$).

In evaluating the validity of (2), it is useful to consider Leffler's extrathermodynamic treatment of linear free-energy relationships,[9] where molecules are divided into a substituent zone, R, and a reaction zone, X. When such a molecule participates in a chemical reaction, the reaction zone is altered from X_r to X_p, while the substituent zone is unchanged. Using this dichotomy, it is apparent that the fundamental assumption basic to the EHP is that only interactions between the substituent zone and reaction zone of the same reactant are important in contributing to differences in the free energy of the transition state. Interactions between the substituent zone of one reactant and the reaction zone of another reactant and interactions between the two reaction or substituent zones are assumed to be either constant or negligible. This is equivalent to restricting transition state interactions to those present in either the products or the reactants.[11] By treating transition state free-energy differences as the sum of individual contributions arising from free-energy differences in the reactants and in the products, eq 2 carries the implication that substituent changes in the reactants influence the properties of the transition state independently of substituent changes in the products. Hence, the validity of (2) depends upon two basic assumptions: (i) α is a single valued, continuous function of ΔF; (ii) the net response of the transition state to simultaneous free-energy changes in both reactants and products is simply the sum of the individual changes. Using these two assumptions, it is possible to show that the relationship between α and ΔF is linear.

If the free energy of the products of some reaction is increased by X units or the free energy of the reactants is lowered by X units, ΔF is unchanged. Since α is single valued, the same value of α will be obtained, regardless of whether the free-energy change occurs at the reactants or the products. The change in α due to an arbitrary unit increase in the free energy of the products ($\delta\alpha_{P\uparrow}$) is identical with the change in α resulting from a corresponding decrease in the free energy of the reactants ($\delta\alpha_{R\downarrow}$) (*i.e.*, $|\delta\alpha_{P\uparrow}| = |\delta\alpha_{R\downarrow}|$). If the free energy of both the products and reactants is increased by an arbitrary unit, ΔF remains the same, and the net change in α is 0. From assumption ii, the net change in α is the sum of the changes in α when the free energy of the reactants and products is changed separately, and hence $\delta\alpha = \delta\alpha_{P\uparrow} + \delta\alpha_{R\rightarrow} = 0$. Therefore $|\delta\alpha_{R\uparrow}| = |\delta\alpha_{P\uparrow}| = |\delta\alpha_{R\downarrow}|$. Let α assume some arbitrary value, α_0, where $0 \leq \alpha_0 \leq 1$. If the free energy of the reactants is increased by an arbitrary unit, α will change from α_0 to α_1. If the free energy of the reactants is increased by another unit, α will change from α_1 to α_2. Since $|\delta\alpha_{R\uparrow}| = |\delta\alpha_{R\downarrow}|$ at α_1, it follows that $\alpha_1 - \alpha_0 = \alpha_2 - \alpha_1$. This relation will hold for α_0 equal to any α, $0 \leq \alpha \leq 1$, and therefore changes in α must be independent of α; hence, dα/dΔF must be constant between $-|\Delta F_{\max}|$ and $+|\Delta F_{\max}|$. Consequently, the relationship between α and ΔF is linear.

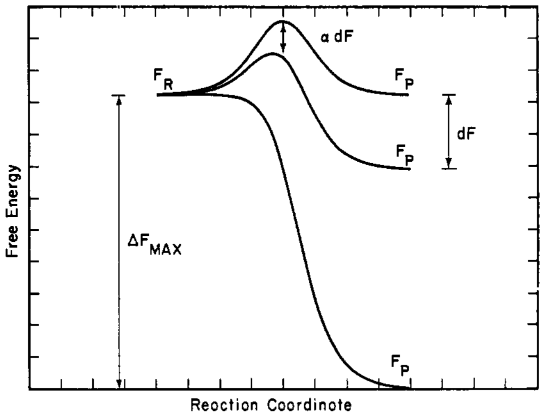

Figure 2. Height of free-energy barrier of a reaction *vs.* ΔF.

Most chemical reactions are accompanied by rearrangement of certain atoms of the reactants as the products are formed. A phrase that frequently appears in connection with this type of atomic motion is "the position of the transition state along the reaction coordinate." This term could be defined as λ, where λ is the fraction of the distance that a participating atom has moved in the transition state from its initial position in the reactants toward the final position which it occupies in the products. Assuming that conditions i and ii apply to λ, the above argument can be used to show that λ must also be a linear function ΔF. When $\Delta F = -|\Delta F_{\max}|$, $\lambda = \alpha = 0$, and for $\Delta F = |\Delta F_{\max}|$, $\lambda = \alpha = 1$. Since λ and α are both linear functions of ΔF and share two common points, they must be equal. It is apparent that

$$\alpha = \Delta F/(2|\Delta F_{\max}|) + {}^1/_2 = \lambda \qquad (3)$$

The equivalence of α and λ is a powerful result, since it requires that all structural changes be equally complete in the transition state. The present analysis shows that whenever some property of the transition state is equally responsive to free-energy changes in the reactants and in the products, it must be a linear function ΔF. Mowery and Streitweiser,[13] Bordwell,[10] and Jencks[20] have discussed the possibility that this condition may not always be valid; that is, in real transition states, some structural changes may "lag behind" others.

Substituting eq 3 into eq 2 and rearranging terms, we get

$$\mathrm{d}\Delta F^* = (\Delta F/2|\Delta F_{\max}| + {}^1/_2)\mathrm{d}\Delta F\cdot \qquad (4)$$

Integrating (4) between $\Delta F = 0$ and $\Delta F = \Delta F_{\max}$, it is seen that

$$\Delta F_0^* = {}^1/_4|\Delta F_{\max}| \qquad (5)$$

This result is quite interesting for several reasons. First, it suggests that the pK range over which the Brønsted slope changes from 0 to 1 will be proportional

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(20) W. P. Jencks, "Catalysis in Chemistry and Enzymology," McGraw-Hill, New York, N. Y., 1969, pp 231–232.

to the barrier height when $\Delta F = 0$. When $\Delta F_0{}^*$ is small, the pK range of the transition will be short. When a large barrier is present, α will pass from its minimum to its maximum over a wide pK range. Qualitatively, this type of behavior has been observed by Eigen.[3] In aqueous proton transfers involving carboxylic acids, ammonium salts, and phenols, the transition region for α_{exp} to change from 0 to 1 is about 7–8 pK units. For weaker acids such as thiols, the range appears to be considerably broader, and the transition is incomplete over a region of at least 10 pK units. For carbon acids the effect is even more pronounced. Pearson and Dillon[21] have compared rate–equilibrium data for various pseudo acids. A series of carbonyl compounds shows a linear Brønsted correlation over a region of about 8 pK units with little hint of curvature. Streitwieser has compared the rates of detritiation of a series of hydrocarbons in methanol–sodium methoxide with the pK's measured using the cesium cyclohexylamide–cyclohexylamine system. The results are interpreted in terms of two straight lines with slopes of 0.37 and 0.58, indicating little change in slope over a span of 18 pK units.[22] Cram and Kollmeyer[23] have similar data for hydrocarbons in DMSO and have observed a change in slope from about 0.5 to 1.0 over a pK range of approximately 10 units. This observation is somewhat tenuous, however, since there are only a limited number of points. Ritchie and Uschold[17] have compiled data correlating exchange rates of hydrocarbons in methanol with estimated methanolic pK's. The transition region appears to cover a span of about 24–30 pK units, but this is not entirely certain since only two compounds are included which are more acidic than methanol. Ritchie's data for pK's and exchange rates in DMSO show a similar broad transition region, but the types of compounds are so varied that there is a degree of uncertainty over the exact nature of the relationship.

The low-energy barrier[3,24] (at Δp$K = 0$) to proton transfer between nitrogen and oxygen systems has several causes, but the ability of hydrogen to form a stable three-center bond is undoubtedly significant in reducing the magnitude of the energy barrier arising when the proton is passed from the donor to the acceptor. Lack of hybridization changes and absence of extensive solvent reorganization are other primary factors.[25] The relatively large barriers for carbon acids result in such a broad transition region that Brønsted relationships will appear linear over wide regions of the pK scale (*e.g.*, 5–10 pK units).

Linear rate–equilibrium relationships have been observed for many other types of reactions,[26] and the present result suggests that curvature in a Brønsted relation will depend more on the type of reaction (*i.e.*, the barrier height at $\Delta F = 0$) rather than the range of reactivity investigated. Related to this is the possibility that $\Delta F_0{}^*$ may be used to characterize a particular reaction type and define a related series of compounds comprising a "Brønsted family." From the relationships expressed by eq 2 and 5 and illustrated in Figure 2, it would be expected that the identity reactions 6 of all compounds fitting the same Brønsted curve should have the same value of ΔF^*.

$$\mathrm{R{-}X_r} + \mathrm{R^*{-}X_p} \rightleftarrows \mathrm{R{-}X_p} + \mathrm{R^*{-}X_r} \tag{6}$$

Marcus has discussed this point and has referred to the activation barrier of an identity reaction as the "intrinsic" barrier since it is independent of ΔF ($\Delta F = 0$ for all identity reactions).[27] Should this concept be supported by experimental data, it would prove quite valuable in characterizing rate–equilibrium relationships.

Equation 4 can be integrated between the limits of $\Delta F = 0$ and $\Delta F = \Delta F$, and substituting eq 5, we get

$$\begin{gathered} \Delta F^* = \Delta F^2/16\Delta F_0{}^* + \Delta F_0{}^* + {}^1\!/_2\Delta F \\ -|\Delta F_{\text{max}}| \leq \Delta F \leq |\Delta F_{\text{max}}| \\ \alpha = \Delta F/8\Delta F_0{}^* + {}^1\!/_2 = \lambda \end{gathered} \tag{7}$$

For the reverse reaction

$$\begin{gathered} \Delta F_{\text{rev}}{}^* = \Delta F^2/16\Delta F_0{}^* - {}^1\!/_2\Delta F + \Delta F_0{}^* \\ -|\Delta F_{\text{max}}| \leq \Delta F \leq |\Delta F_{\text{max}}| \\ \beta = {}^1\!/_2 - \Delta F/8\Delta F_0{}^* = 1 - \lambda \end{gathered} \tag{8}$$

Equations 7 and 8 are useful results since they are quantitative statements of the EHP in terms of ΔF and ΔF^* rather than relative differences of free-energy quantities.

Equations 7 and 8 express the relationship between rate and equilibrium for any reaction obeying i, ii. It is noteworthy that Marcus has derived an equation identical with (7) using an entirely different approach. Marcus' treatment is valid for electron-transfer reactions where there is weak overlap between the electronic orbitals of the reactant molecules in the activated complex.[28] Marcus proposes that electron-transfer reactions proceed through two successive intermediate states, X* and X, which have the same atomic configurations but different electronic configurations. His quantum mechanical argument shows that if there is zero overlap between the orbitals of the reactants in each of these states, then the energy of the two states must be the same.[28a] Marcus treats the first state, X*, as having the solvent orientation of the products while possessing the atomic configuration of the reactants. Since the solvent molecules surrounding X* are not at equilibrium, Marcus uses a derived equation for the electrostatic free energy of nonequilibrium states to calculate the free energy of all possible states. The most probable state is determined by minimizing the free energy subject to the constraint that the energy of X* and X must be equal.[28a] The end result is Marcus' equation[28k]

$$\Delta F^* = \lambda(1 + \Delta F_{\text{R}}{}^{0\prime}/\lambda)^2/4 \tag{9}$$

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[22] A. Streitwieser, Jr., W. B. Hollyhead, A. H. Pudjaatmaka, P. H. Owens, T. L. Kruger, P. A. Rubenstein, R. A. MacQuarrie, M. L. Brokaw, W. K. C. Chu, and H. M. Niemeyer, *ibid.*, **93**, 5088 (1971).

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[25] C. D. Ritchie, *J. Amer. Chem. Soc.*, **91**, 6749 (1969).

[26] (a) E. Lieber, C. N. Ramachandra, Rao, and T. S. Chao, *ibid.*, **79**, 5962 (1957); (b) B. M. Anderson and W. P. Jencks, *ibid.*, **82**, 1773 (1960); (c) J. N. Brønsted and K. J. Pedersen, *Z. Phys. Chem.*, **108**, 185 (1924).

[27] R. A. Marcus, *J. Phys. Chem.*, **72**, 891 (1968).

[28] (a) R. A. Marcus, *J. Chem. Phys.*, **24**, 966 (1956); (b) *ibid.*, **24**, 979 (1956); (c) *ibid.*, **26**, 867 (1957); (d) *ibid.*, **26**, 872 (1957); (e) *Can. J. Chem.*, **37**, 155 (1959); (f) *Discuss. Faraday Soc.*, **29**, 21 (1960); (g) *J. Phys. Chem.*, **67**, 85 2889 (1963); (h) *Annu. Rev. Phys. Chem.*, **15**, 155 (1964); (i) *J. Chem. Phys.*, **43**, 679 (1965); (j) *Exch. React. Proc. Symp.*, 1 (1965); (k) *J. Phys. Chem.*, **72**, 891 (1968); (l) A. O. Cohen and R. A. Marcus, *ibid.*, **72**, 4249 (1968).

By substituting $\lambda = 4\Delta F_0^*$ and $\Delta F_R^{0\prime} = \Delta F$, it is seen that the Marcus equation is identical with (7). The basis for Marcus' equation is the assumption of zero overlap between orbitals of the reactants in the activated complex. Since this is equivalent to the assumption inherent in the development of (7), namely, that interactions between reactants in the transition state are negligible or constant, it is not surprising that the two seemingly different treatments converge to the same result.

Although many of the basic ideas expressed in the development of the EHP have been previously discussed by Marcus,[27,28] it is worthwhile to cover the same ground from a different approach. The development of eq 7 *via* Hammond's postulate links a qualitative and intuitive concept with the elegant and highly mathematical results of Marcus. Marcus has shown[27] that the bond energy–bond order (BEBO) method[29] is nearly identical with his own proposal. The present work provides further unification of the rate-equilibrium concept by demonstrating that Hammond's postulate and Marcus' theory lead to equivalent results.

Cohen and Marcus have applied (9) to experimental data from 16 proton and atom-transfer reactions.[261] The results appear to be consistent with this equation, although the authors caution that more experimental data is needed. Nonetheless, it is quite remarkable that such a simple concept seems to hold for these various reactions. Although equation 7 is a good approximation for many reactions, it definitely has its limits, such as in the nitroalkane example.[10] Whether this case involves additional interactions in the transition state as Kresge[11] and Streitwieser[22] suggest, or nonsynchronous structural changes (*i.e.*, $\alpha \neq \lambda$ for all structural changes) as implied by Bordwell, *et al.*,[10] and Mowery and Streitwieser[13] is debatable. Marcus' suggestion that the intrinsic barrier (ΔF_0^*) is substituent dependent is also possible.[12] These limitations of rate-equilibrium relationships are all inherent deviations in that they involve a breakdown of i, ii and (7). Other limitations that appear even if the EHP is an exact model will now be discussed.

It is possible to use (7) and (8) to develop a proton-transfer model based on the extended Hammond's postulate. In order to do this, three assumptions will be used. 1. Eigen's three-step mechanism is general for carbon acids as well as for oxygen and nitrogen acids. 2. The EHP is valid for the proton-transfer step (k_b and k_{-b}). 3. The encounter rate constants are independent of ΔpK.

If K_A is the observed equilibrium constant, then

$$\log k_A = \log\left((k_a k_b k_c)/(k_{-a} k_{-b} k_{-c})\right) \qquad (10)$$

Assuming that changes in k_{obsd} depend only on k_b and k_{-b}, an expression for α_{exp} can be derived using (1) and (10).

$$\alpha_{exp} = \frac{d \log k_{obsd}}{d \log K_A} = \frac{d \log k_{obsd}}{dk_b} \cdot \frac{dk_b}{d \log K_A}$$

$$\alpha_{exp} = \frac{k_{-b}\left(k_{-a}(k_{-b} + k_c)\dfrac{dk_b}{dk_{-b}} - k_b k_{-a}\right)}{(k_{-a}(k_{-b} + k_c) + k_b k_c)\left(k_{-b}\dfrac{dk_b}{dk_{-b}} - k_b\right)} \qquad (11)$$

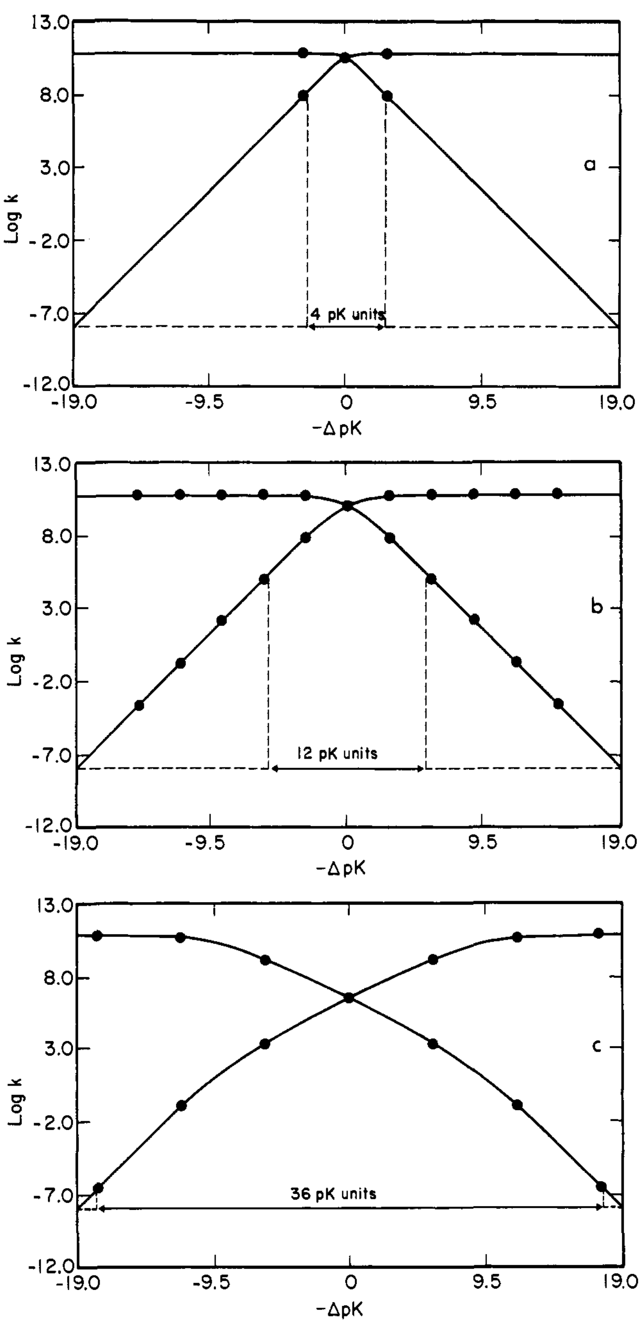

Figure 3. Effect of barrier height at $\Delta F = 0$ on transition region. $k_a = k_{-c} = 6 \times 10^{10}$, $k_{-a} = k_c = 6 \times 10^9$. (a) $\Delta F_0^* = 1$ kcal/mol. (b) $\Delta F_0^* = 5$ kcal/mol. (c) $\Delta F_0^* = 10$ kcal/mol.

The only problem in evaluating (11) is the derivative term, dk_b/dk_{-b}. It can be calculated using the extended Hammond's postulate. From transition state theory and (7) and (8)

$$k_b = \kappa T/he^{-\Delta F^*/RT} = \kappa T/he^{-(\Delta F^2/16\Delta F_0^* + {}^1/{}_2\Delta F + \Delta F_0^*)/RT}$$

$$k_{-b} = \kappa T/he^{-\Delta F_{rev}^*/RT} = \kappa T/he^{-(\Delta F^2/16\Delta F_0^* - {}^1/{}_2\Delta F + \Delta F_0^*)/RT}$$

$$\frac{dk_b}{dk_{-b}} = (e^{-\Delta F/RT})(\Delta F/\Delta F_0^* + 4)/(\Delta F/\Delta F_0^* - 4) \qquad (12)$$

This completes the derivation of the proton-transfer model based on Hammond's postulate. The experimental quantities k_{for}, k_{rev}, and α_{exp} can now be cal-

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(29) H. S. Johnston and C. Parr, *J. Amer. Chem. Soc.*, **85**, 2544 (1963).

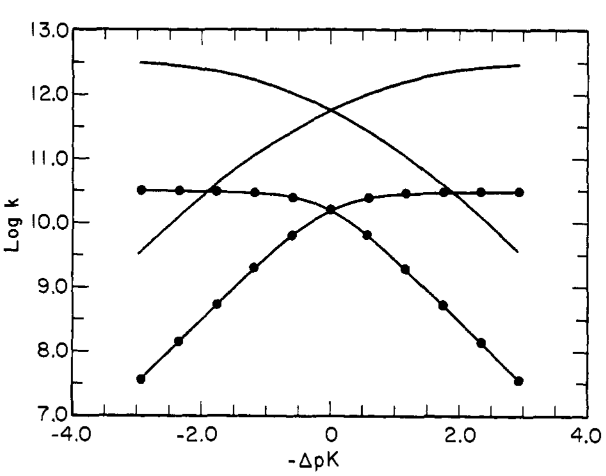

Figure 4. Damping effect of diffusion steps on observed rate. Upper curves: k_b and k_{-b} *vs.* $-\Delta pK$. Lower curves: k_{for} and k_{rev} *vs.* $-\Delta pK$. Note that when $\alpha = 0.3$, α_{exp} is still nearly zero. The circles on the lower curve are spaced in units of 0.1α starting with $\alpha = 0.0$. $\Delta F_0^* = 1$ kcal/mol, $k_a = k_{-c} = 6 \times 10^{10}$, $k_c = k_{-a} = 6 \times 10^9$.

culated as a function of the diffusion rate constants, ΔF and ΔF_0^*, and compared with k_b, k_{-b}, and α.

From Figure 3, it can be seen that the transition region for α_{exp} to change from 0 to 1 broadens as the barrier height at $\Delta pK = 0$ increases. It is interesting that the transition region is considerably less than that predicted by (5). The reason for this is that proton transfer (k_b) is initially faster than encounter (k_a) so that the encounter step exerts a damping effect on the observed rate. This is illustrated in Figure 4. Note that α is steadily increasing from 0 toward 1, while α_{exp} remains near 0 until k_b becomes rate limiting. The effect of the barrier height at $\Delta pK = 0$ on this damping phenomenon is quite surprising. WhenΔ F_0^* increases from 1 kcal to 5 kcal, the damping on α_{exp} increases, and then it decreases as ΔF_0^* is raised to 10 kcal. For the low barriers (*e.g.*, 1 and 5 kcal) proton transfer is not quite rate limiting at $\Delta pK = 0$. The change in rate from $\alpha_{exp} = 0$ to $\alpha_{exp} = 0.5$ is about the same for both barriers due to the damping effect, while the change is spread out over a larger pK range for the 5-kcal barrier. Since $\alpha_{exp} = -d \log k_{obsd}/d\Delta pK$, the damping effect exerts a larger distortion of the slope for the 5-kcal barrier than the 1-kcal barrier. As ΔF_0^* is increased to 10 kcal, proton transfer becomes rate limiting much sooner (*i.e.*, at large values of $|\Delta pK|$), and α_{exp} is closer to α. This effect of ΔF_0^* on the damping phenomena will be observed whenever k_b is still appreciably faster than k_{-a} near $\Delta pK = 0$. Values of α and α_{exp} from Figure 3 are tabulated in Table I.

Internal return will also play an important role in determining the breadth of the transition region and the magnitude of the damping effect. When k_c/k_{-b} or k_{-a}/k_b is small, internal return will be significant, and the transition region will tend to decrease, resulting in a sharper transition of α_{exp} from 0 to 1. This is shown in Figure 5. It is highly important to realize that a change in k_c, for example, is felt over the entire pK range and not just in the region where k_c is rate limiting. The reason for this is quite simple. For the reverse reaction, k_{-c} will be the rate-determining step at low values of ΔpK and the observed rate will be at its maximum. As the ratio k_c/k_{-b} increases, k_{rev} will approach $(k_{-c}/k_c) \cdot k_{-b}$ and start to decrease as ΔpK increases. For a given value of ΔF_0^* and k_{-c}, the maximum rate will be maintained over a longer pK range as k_c is decreased. In Figure 5 k_c is changed from 10^9 to 10^6 and throughout the transition region, k_{obsd} is higher for the lower value of k_c. Note that the slope (β_1) for $k_c = 10^6$ is initially closer to 0 than the slope (β_2) when $k_c = 10^9$. Because β_1 is less than β_2 for low values of ΔpK, β_1 must at some point exceed β_2 since as ΔpK increases, k_{-a} will eventually become the rate-limiting step and both slopes will approach unity. Not until ΔpK increases from a low negative number to a high positive number (when k_{-a} is rate limiting) will β_1 equal β_2. Thus the effect of changing k_c is felt throughout the entire transition of α_{exp} from 0 to 1 and not just the region where k_c is rate limiting for the forward reaction.

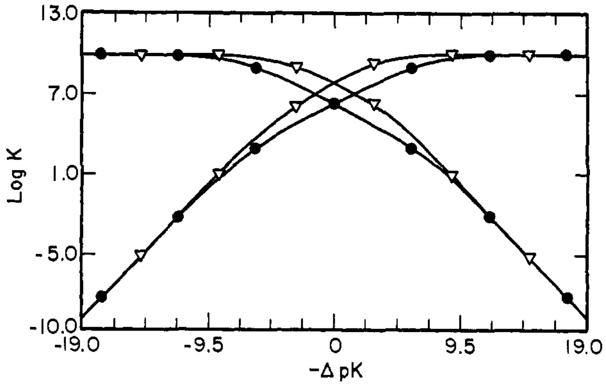

Figure 5. Effect of internal return on the Brønsted slope. Circles are spaced in units of 0.1α, starting with $\alpha = 0.2$. $k_a = k_{-c} = 10^{10}$, $k_{-a} = 10^9$, $\Delta F_0^* = 10$ kcal/mol. Lower curve: $k_c = 10^9$. Upper curve: $k_c = 10^6$.

Table I. α and α_{exp} *vs.* Barrier Height[a]

	α_{exp}			Log k_b		
α	1 kcal	5 kcal	10 kcal	1 kcal	5 kcal	10 kcal
0.1	0.005	0.000	0.000	12.8	12.6	12.5
0.2	0.007	0.001	0.003	12.7	12.2	11.6
0.3	0.063	0.006	0.090	12.5	11.5	10.2
0.4	0.206	0.074	0.391	12.3	10.5	8.2
0.5	0.500	0.500	0.500	12.1	9.1	5.5
0.6	0.794	0.927	0.608	11.7	7.5	2.2
0.7	0.937	0.993	0.909	11.3	5.5	−1.7
0.8	0.983	0.999	0.997	10.9	3.5	−5.8
0.9	0.995	1.000	1.000	10.4	1.0	−10.8

[a] Log k_{-b} at α equals log k_b at $1 - \alpha$.

Another type of deviation can occur if k_a and k_{-c} are not equal. Eigen[3] has observed this in cases where the products hydrogen bond to a different degree than the reactants or where the charge type of the base in the forward direction is different from that of the reverse reaction.

This is illustrated in Figure 6 (see Table II) for the case where k_a is less than k_{-c}. As internal return for the reverse reaction increases (k_{-a} decreases), the transition region shortens, and α_{exp} is damped at high and low values. However, at $\Delta pK = 0$, α_{exp} is still close to 0.5. When internal return for the forward reaction is high, an additional effect is observed. As k_{-a} decreases, the lines for the forward and reverse reactions intercept

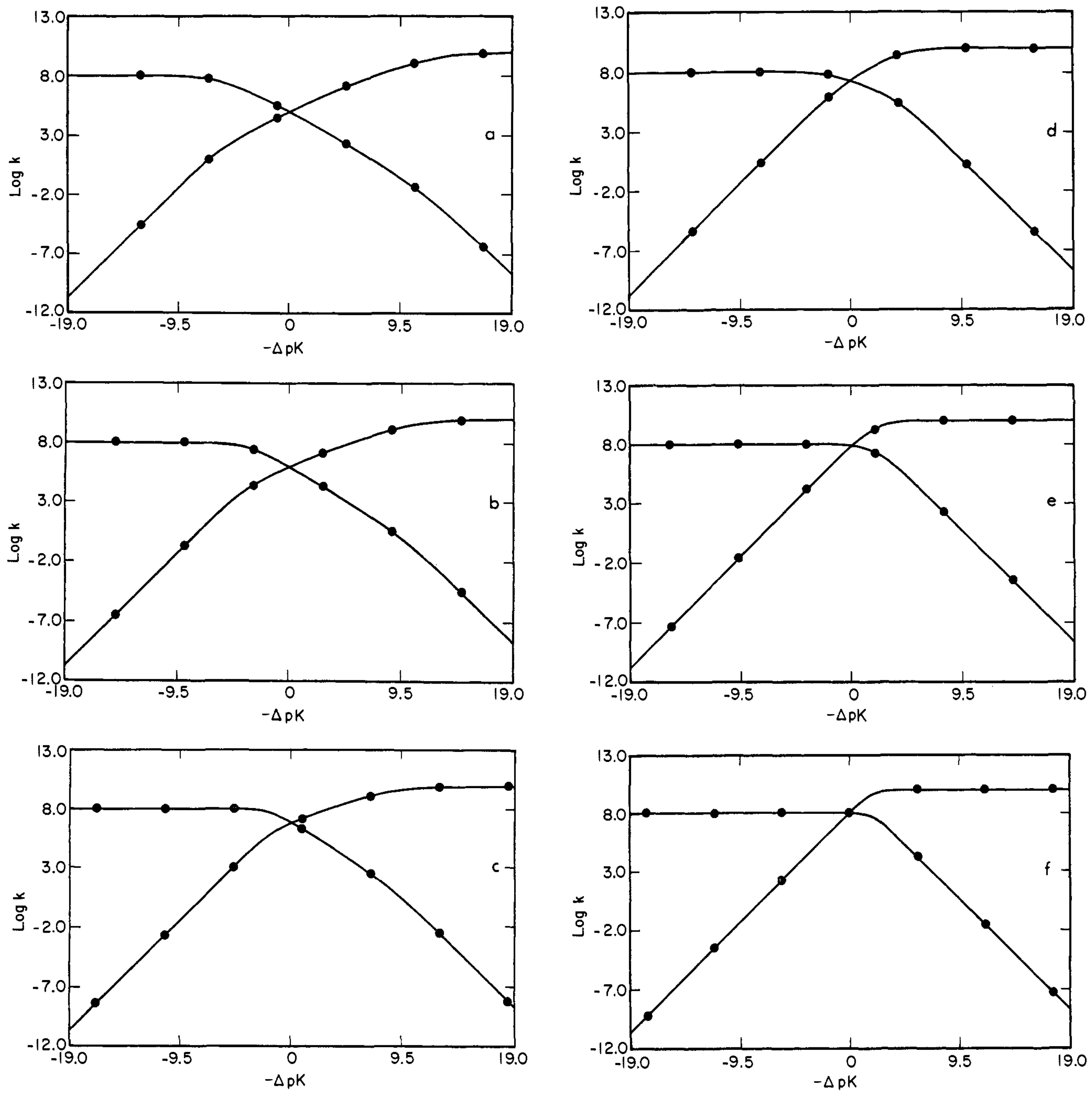

Figure 6. Effect of internal return on α_{exp}. See Table II.

each other at lower values of α_{exp}. The result is a low value of α_{exp} at $\Delta pK = 0$ (or a high value of β_{exp}). Traditionally it has been assumed that α_{exp} will be near $^1/_2$ at $\Delta pK = 0$, yet it is apparent that the encounter steps can distort α_{exp} to as low as 0. In Figure 7 a case is considered which dramatically points out what a serious effect the encounter steps can exert on α_{exp}. Using $\Delta F_0{}^* = 14$ kcal/mol, $k_a = 10^3$, $k_{-a} = 10^{11}$, $k_c = 10^6$, and $k_{-c} = 10^9$, α_{exp} at $\Delta pK = 0$ is found to be about 0.38. Furthermore, the transition region is quite broad and the plot appears to be nearly linear in this section. For comparison, the points from Ritchie's[16] Brønsted correlation for hydrocarbons in methanol are included. It should be stressed that no significance can be attached to the parameters used in generating this plot since they can be altered by an order of magnitude or two without drastically changing the features of the curve. Since only two points more acidic than methanol are included, one of which shows considerable structural differences from the other compounds, the significance of the experimental curvature is in doubt, and hence it would not be justified to attempt either a refined fit of the data or to assign mechanistic significance to the parameters. The experimental points are included only to show that the parameters chosen can lead to a Brønsted relation that is not unreasonable and that a linear Brønsted plot with a slope considerably different from $^1/_2$ near $\Delta pK = 0$ is not necessarily the result of a deviation from the extended Hammond's postulate. The present purpose of the model is not to fit experimental data by adjustable parameters, but merely to demonstrate that under certain circumstances encounter of the reactants and separation of the products can be just as important in

Table II. α_{exp}[a]

α	$k_c = 10^{11}$ $k_{-a} = 10^8$	$k_c = 10^{11}$ $k_{-a} = 10^6$	$k_c = 10^{11}$ $k_{-a} = 10^4$	$k_c = 10^6$ $k_{-a} = 10^8$	$k_c = 10^6$ $k_{-a} = 10^6$	$k_c = 10^6$ $k_{-a} = 10^4$
0.0	0.000	0.000	0.000	0.000	0.000	0.000
0.1	0.000	0.000	0.000	0.000	0.000	0.000
0.2	0.000	0.000	0.000	0.000	0.000	0.000
0.3	0.002	0.000	0.000	0.002	0.000	0.000
0.4	0.176	0.003	0.000	0.176	0.003	0.000
0.5	0.499	0.386	0.016	0.612	0.500	0.026
0.6	0.601	0.600	0.590	0.997	0.997	0.997
0.7	0.738	0.738	0.738	1.000	1.000	1.000
0.8	0.961	0.961	0.961	1.000	1.000	1.000
0.9	0.997	0.997	0.997	1.000	1.000	1.000
1.0	1.000	1.000	1.000	1.000	1.000	1.000
α_{exp} at $\Delta pK = 0$	0.51	0.55	0.56	0.35	0.11	0.03
Internal return, reverse rxn	Low	Medium	High	Low	Medium	High
Internal return, forward rxn	Low	Low	Low	High	High	High
Figure	6a	6b	6c	6d	6e	6f

[a] It is seen that α_{exp} has little dependence on k_{-a} at high values of α and little dependence on k_c at low values of α. This does not contradict the results from Figure 5, since α does not correspond to the same value of $-\Delta pK$ for each of the vertical columns in Table II. A comparison of α_{exp} at identical values of $-\Delta pK$ does show a dependence on k_{-a} and k_c over the entire transition region. It can be shown that k_c (k_{-a}) factors out of the expression for α_{exp} at low (high) values of α_{exp}. For a given $\Delta F_0{}^*$, k_b and k_{-b} will be uniquely determined by α. Thus at constant α, α_{exp} will be independent of k_c (k_{-a}) at low (high) values of α_{exp}. However, at any given value of $-\Delta pK$, k_b or k_{-b} is dependent on k_c and k_{-a}, and therefore α_{exp} retains its dependence on k_c and k_{-a} throughout the transition region.

determining the slope of a Brønsted plot as free-energy differences. Experiments are now in progress that will help assess the relative importance of these two factors with regard to the Brønsted behavior of carbon acids.

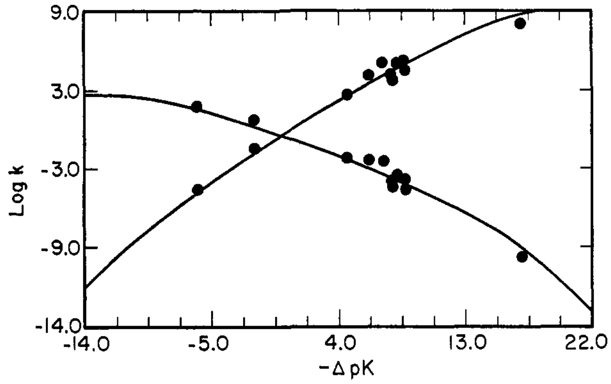

Figure 7. Effect of diffusion steps on α_{exp}. $\Delta F_0{}^* = 14$ kcal/mol, $k_a = 10^3$, $k_{-a} = 10^{11}$, $k_c = 10^6$, $k_{-c} = 10^9$. Note that α_{exp} is only about 0.38, while α is 0.5, at $\Delta pK = 0.0$, and that the line is nearly linear in this region.

When internal return is low ($k_{-a} \gg k_b$, $k_c \gg k_{-b}$ for α_{exp} between 0 and 1), $\Delta F_0{}^*$ is high, and k_a and k_{-c} are larger than k_b and k_{-b} over most of the transition region, α_{exp} will be a good approximation to α. But before any significance can be attributed to α_{exp} regarding transition state structure, it is absolutely necessary to know how the encounter rate constants (k_a, k_{-a}, k_c, k_{-c}) influence the Brønsted slope, even if they do not have any effect on relative values of k_{obsd}. That prior and subsequent steps can affect the slope of a Brønsted plot, without altering relative reactivities, is a highly significant point that cannot be emphasized too strongly.

Since a Brønsted plot expresses a relation between free-energy differences of two reactions, it is conceivable that the present results may apply to free-energy relationships in general, particularly since entirely different reactions, solvents, and temperatures are often involved.

The model developed in this paper has extended Hammond's postulate to allow a quantitative definition of transition state structure and of the relationship between ΔF^* and ΔF. The consequences of this postulate can now be precisely defined, facilitating a test of the validity of this fundamental concept.

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