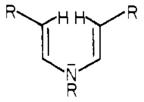
of cis–trans isomers of **3** and **4**. These isomers can be generated only in a ground-state back reaction of ZW since it was shown above that cis–trans isomerization in the excited triplet state (^{3}EA*) occurred only in ether as a solvent.

One may be tempted to apply the above considerations also to the ring-opening reaction of dihydrocarbazole **14**. However, the activation energy (67 kJ/mol) and frequency factor (10^{13} s^{-1}) of this reaction do not exhibit extraordinary values.[7] Obviously, the four additional π electrons which the DHC system contains compared with ZW systems cannot be neglected in the molecular orbital considerations. It is, therefore, not possible to draw general conclusions by reducing the problem to considering a divinylamine system (**15**) which is isoelectronic with the cyclopentadienyl anion.



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Also, the other ZW decay mode, H migration (k_6), does not show the same kinetic behavior for all enamines investigated, though in ether, where hydrogen shift is the only detectable decay mode, the frequency factors are relatively close to each other (Table I). In MCH, however, the activation energies range from 55 kJ/mol in the case of **5** to practically zero in the case of **6** while the corresponding frequency factors are 10^9 and 2.4 s^{-1} (Table II). Nevertheless, extraordinary constants for k_6 were not entirely unexpected, since the analogous reaction of DHC also proceeds with zero activation energy[7] at a rate of 1.2 s^{-1}. Further peculiarities of H migration in DHC systems will be discussed in a forthcoming paper.[5]

The fact that ring opening was found only in MCH and not in ether indicates a stabilizing effect which a more polar solvent may have on zwitterionic intermediates. On the other hand, this is probably a small effect since the analogous reactions of DHC[7] are obviously independent of the polarity of the solvent. One may expect, therefore, that even in the system studied in this paper ring opening can occur in the more polar solvents whenever it is possible to extend the temperature range somewhat beyond the boiling point of ether.

A brief consideration of possible viscosity effects should perhaps be added. The changes of the quantum yields of the products appear in a temperature region (see Figure 4b) in which no dramatic changes of the viscosities of both the solvents are known so that monomolecular reactions such as ring opening and hydrogen migration will not be affected. Rather the temperature dependence of the ratio k_{ct}/k_2 (Scheme I) may be influenced by rising viscosity as the temperature approaches the melting point of ether (cf. Figure 2a). However, since an Arrhenius diagram of k_2 in the case of the cyclic enamine **1** between room temperature and −85 °C gives a straight line[5b] in ether as a solvent, a viscosity effect on k_2 is also unlikely for the reactions of the acyclic enamines **2**–**4**. Therefore, there is no obvious interdependence of rate constants and quantum yields on solvent viscosity.

Conclusions

The evidence presented here warrants the following generalizations: photocyclization yields of *N*-aryl enamines (Scheme I) depend on the molecular structure of the enamines, on temperature, and on solvent. At room temperature in nonpolar solvents high yields are expected for cyclic enamines (Scheme I, R_1 and R_2 being connected in a ring system). For acyclic enamines lower temperatures are preferable in order to suppress ring-opening back reactions. When possible, polar solvents should be used because of their stabilizing effect on the intermediate zwitterions. Irradiation of unsymmetrically substituted enamines like **3** and **4** may give mixtures of stereoisomers of the products due to reirradiation of cis–trans isomerized educts formed by back reactions.

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Use of Kinetic Isotope Effects in Mechanism Studies. Effect of an Internal Return Mechanism on the Arrhenius Behavior of Primary Hydrogen Isotope Effects[1a]

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Abstract: The effect of an internal return mechanism when the return step, k_{-1}, competes favorably with the product-forming step, k_2, on Arrhenius behavior of primary kinetic isotope effects has been modeled. The kinetic expression, $k_{obsd} = k_1k_2/(k_{-1} + k_2)$, for this situation cannot neglect either k_{-1} or k_2 and one would therefore expect to observe anomalous Arrhenius behavior. To analyze the expected temperature-dependence profile of k^H/k^D, we set $k_2^H = k_2^D$ (assuming a negligible isotope effect for the second step), replaced individual rate constants by the appropriate Arrhenius expression, and set $A_i^H = A_i^D$. Solutions of the equation allow modeling of effects and they have generated both normal and anomalous behavior. Most of the plots are linear in temperature regions normally used in kinetic studies. Of interest are solutions that predict temperature-independent isotope effects as well as Arrhenius behavior that mimics the experimental criteria for detecting quantum-mechanical tunneling.

The use of primary kinetic isotope effects in the study of organic reaction mechanisms has been well documented over the past 20 years,[2-5] and experimental techniques have improved and theory has developed to the point where the magnitude of the isotope effect has been used to describe transition-state structures. When observed effects differ from the theoretically expected maximum, it becomes increasingly important to be able to differentiate be-

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(1) (a) Presented in part at the IUPAC Fourth International Symposium on Physical Organic Chemistry, York, England, Sept 4–8, 1978; (b) Ithaca College; (c) The Pennsylvania State University, Wilkes-Barre Campus.

(2) (a) L. Melander, "Isotope Effects on Reaction Rates", Ronald Press, New York, 1960. (b) Reference 2a, pp 24–32.

(3) F. H. Westheimer, *Chem. Rev.*, **61**, 265–273 (1961).

(4) R. P. Bell, *Chem. Soc. Rev.*, **3**, 513–544 (1974).

(5) R. A. More O'Ferrall in "Proton-Transfer Reactions", E. F. Caldin and V. Gold, Eds., Chapman and Hall, London, 1975.

Table I. Kinetic Isotope Effects (25 °C), ΔE_a, A^H/A^D Ratios, and Swain–Schaad Exponents (y at 25 °C) for Alkoxide-Promoted Elimination Reactions

compd	k^H/k^D	ΔE_a, kcal mol^{-1}	A^H/A^D	y^a
p-$ClC_6H_4CLBrCF_2Br$	3.73^c	0.5	1.5	
$C_6H_5CLBrCF_2Br$	4.00^c	0.1	3.0	2.39
$C_6H_5CLClCF_2Cl$	3.06^b	−0.3	4.8	2.14
$C_6H_5CLClCF_2Cl$	2.35^c	0.0	2.4	1.94
p-$ClC_6H_4CLClCF_2Cl$	2.21^c	0.1	2.1	
$C_6H_5CLBrCH_2Br$	4.34^c	0.0	4.3	
$C_6H_5CL(CH_3)CH_2Br^d$	7.82^b	1.7	0.4	2.08
$C_6H_5CL_2CH_2Br^e$	7.51^b	1.6	0.5	

^{a} Defined for $k^H/k^D = (k^D/k^T)^y$. ^{b} EtONa–EtOH. ^{c} MeONa–MeOH. ^{d} Reference 26a. ^{e} Reference 27.

Scheme I

$$\gt C\text{-}L + \bar{O}R \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} \gt C^{-}\cdots L\text{–}OR \xrightarrow{k_2} \text{elimination or exchange products}$$

tween alternate mechanisms that could account for these variances. Primary hydrogen isotope effects should arise from a difference in zero-point energies between C–L bonds (L = H, D, or T) in the ground state and transition state. A maximum effect would be measured when there is no residual zero-point energy difference between isotopically labeled substrates in the transition state. For such a case, the activation energy difference, $\Delta E_a = E_a^D - E_a^H$, would equal the ground-state zero-point energy difference, $E_0^D - E_0^H$. Since the Arrhenius preexponential factor, A, should be nearly equal for isotopically labeled compounds, a maximum effect can be calculated from the energy term:[6]

$$k^H/k^D = \exp(\Delta E_a/RT) \tag{1}$$

Smaller effects are normally attributed to reactions that proceed through asymmetric transition states which have residual zero-point energy differences.[2b,3] This has led to correlating the amount of proton transfer in the transition state with the magnitude of the kinetic isotope effect.[7] Arrhenius behavior should be normal in such cases with observed A^H/A^D ratios of about 1 and observed ΔE_a less than that predicted by zero-point energy differences of the substrate, and k^H/k^D should still follow eq 1 for any temperature. Larger than maximum effects have been explained by evoking the quantum-mechanical tunnel effect, which can be experimentally detected by observing anomalous Arrhenius behavior of the rate ratio, k^H/k^D over a given temperature range.[4] When a tunneling correction is necessary, the observed $\Delta E_a > E_0^D - E_0^H$ and $A^H/A^D < 0.6$.

We have recently reported anomalous Arrhenius behavior for a number of elimination reactions where hydrogen isotope effects, k^H/k^D, are between 2.2 and 4.3, but the observed $\Delta E_a \simeq 0$, Table I.[8] The effects appear to come from A^H/A^D ratios greater than 2. These results show dramatically that care must be taken when interpreting single temperature isotope effects, since this Arrhenius behavior could not be attributed to a single-step mechanism with an asymmetric transition state. The desire to understand this highly unusual Arrhenius behavior has initiated our current investigations. The internal return mechanism shown in Scheme I is an alternate explanation for smaller than maximum effects.[9] Streitwieser et al.[10] have proposed that the use of all three isotopes of hydrogen can in principle allow the calculation of the amount of internal return for each labeled compound, $a^L = k_{-1}{}^L/k_2$.[11] Their approach is based on a deviation of experimental results from the Swain–Schaad equation,[12] $k^H/k^D = (k^D/k^T)^y$, where y can be 2.26 or 2.344 depending on the assumptions made in the derivation.

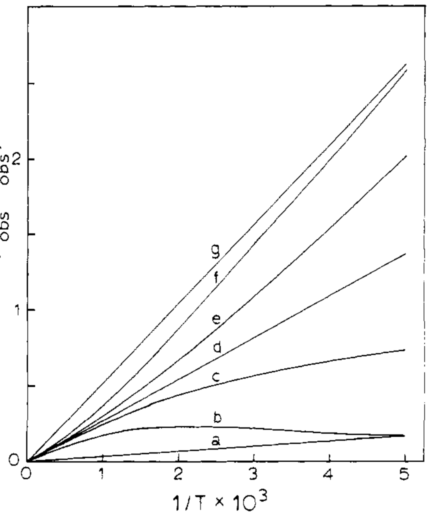

Figure 1. Ln ($k^H{}_{obsd}/k^D{}_{obsd}$) vs. $1/T$; $\Delta H_1{}^D - \Delta H_1{}^H$ = 46 cal/mol; A_2/A_{-1} = 1.0; $E_{-1}{}^D - E_{-1}{}^H$ = 1000 cal/mol; $E_{-1}{}^H - E_2$ = (a) −10 000, (b) −2000, (c) −1000, (d) −500, (e) 0, (f) 1000, and (g) 10 000 cal/mol.

The Streitwieser treatment is for single-temperature measurements and we were interested in predicting the temperature dependence of observed k^H/k^D values when reaction proceeds by a two-step mechanism where neither the first nor second step in Scheme I is clearly rate limiting. Equations for observed "free energy" of activation in complex and reversible reactions have been treated by Kreevoy;[13] however, this treatment has not been extended to cover Arrhenius behavior of isotope effects. The kinetic expression for an internal return mechanism is

$$k_{obsd} = \frac{k_1 k_2}{k_{-1} + k_2} = \frac{K_1 k_2}{1 + (k_2/k_{-1})}, \text{ where } K_1 = k_1/k_{-1}$$

If one assumes a negligible isotope effect for the second step, $k_2{}^H \simeq k_2{}^D$, then the expression for the observed kinetic isotope effect can be written

$$\frac{k^H{}_{obsd}}{k^D{}_{obsd}} = \frac{K_1{}^H(1 + (k_2/k_{-1}{}^D))}{K_1{}^D(1 + (k_2/k_{-1}{}^H))} \tag{2}$$

The assumption of a negligible isotope effect for step 2 is not necessary for our treatment; however, it was made by Streitwieser et al.[10] and does simplify the equations, so we will continue to use it in our model. If the individual rate constants are replaced by the appropriate Arrhenius expression, $k_i = A_i \exp(-E_i/RT)$, then $A_i{}^H = A_i{}^D$ in accord with isotope theory, and if the logarithm is taken of both sides, eq 2 becomes

$$\ln\frac{k^H{}_{obsd}}{k^D{}_{obsd}} = \left[\frac{(E_1{}^D - E_{-1}{}^D) - (E_1{}^H - E_{-1}{}^H)}{RT}\right] + \ln\left[\frac{1 + (A_2/A_{-1})\exp((E_{-1}{}^D - E_2)/RT)}{1 + (A_2/A_{-1})\exp((E_{-1}{}^H - E_2)/RT)}\right] \tag{3}$$

Equation 3 can be used to model experimental data by adjusting

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[6] Schneider and Stern [M. E. Schneider and M. J. Stern, *J. Am. Chem. Soc.*, **94**, 1517–1522 (1972)] considered a variety of model reactions and showed that A^H/A^D was always between 0.7 and 1.2 for a temperature range 20–2000 K, and had an absolute minimum value of 0.5.

[7] Reference 5, pp 216–227.

[8] H. F. Koch, D. B. Dahlberg, M. F. McEntee, and C. J. Klecha, *J. Am. Chem. Soc.*, **98**, 1060–1061 (1976).

[9] D. J. Cram, "Fundamentals of Carbanion Chemistry", Academic Press, New York, 1965, pp 27–29.

[10] A. Streitwieser, Jr., W. B. Hollyhead, G. Sonnichsen, A. H. Pudjaatmaka, C. J. Chang, and T. C. Kruger, *J. Am. Chem. Soc.*, **93**, 5096–5102 (1971).

[11] Reference 10 does not include a formula to calculate a^H or a^D. This will appear in D. W. Boerth and A. Streitwieser, Jr., *J. Am. Chem. Soc.*, submitted for publication.

[12] C. G. Swain, E. C. Stivers, J. F. Reuwer, Jr., and L. J. Schaad, *J. Am. Chem. Soc.*, **80**, 5885–5893 (1958).

[13] M. M. Kreevoy in "Technique of Organic Chemistry", Vol. 8, Part II, 2nd ed., A. Weissberger, Ed., Wiley-Interscience, New York, 1963, pp 1371–1374.

Table II. Results of Calculations Using Equation 3 to Simulate k^H/k^D and k^D/k^T

curve[a]	$(E_{-1}{}^H - E_2)$,[b] cal mol^{-1}	k^H/k^D 20 °C	k^D/k^T 20 °C	calcd $E_a{}^D - E_a{}^H$,[c] cal mol^{-1}	calcd A^H/A^D [c]	calcd internal return[d] a^H	a^D	a^T
(a)	−10 000	1.08	1.03	46	1.00			
(b)	− 2000	1.24	1.20	−33	1.31	25 (31)	4.9 (5.6)	2.5 (2.7)
(c)	− 1000	1.83	1.59	214	1.27	5.5 (5.6)	0.99 (1.0)	0.48 (0.48)
(d)	− 500	2.55	1.82	546	1.00	2.4 (2.4)	0.42 (0.42)	0.20 (0.20)
(e)	0	3.55	1.98	898	0.76	0.99 (1.0)	0.18 (0.18)	0.09 (0.09)
(f)	1000	5.27	2.11	1135	0.75	0.16 (0.18)	0.03 (0.03)	0.01 (0.02)
(g)	10 000	6.02	2.15	1045	1.00			

[a] Letters refer to the curves shown in Figure 1. [b] Values for the parameters: $\Delta H_1{}^D - \Delta H_1{}^H = 46$; $\Delta H_1{}^T - \Delta H_1{}^D = 20$; $E_{-1}{}^D - E_{-1}{}^H = 1000$; $E_{-1}{}^T - E_{-1}{}^D = 427$; $A_2/A_{-1} = 1.0$. [c] The calculated values of k^H/k^D between 0 and 50 °C at 10 °C intervals were used. [d] $a^L = k_{-1}{}^L/k_2$; see ref 10 and 11. Numbers in parentheses are calculated using eq 4 with $A_2/A_{-1} = 1.0$.

four parameters. Two of the parameters are related to the magnitude of the true isotope effect of the proton-transfer step: (i) $\Delta H_1{}^D - \Delta H_1{}^H$,[14] the equilibrium isotope effect for step 1, and (ii) $E_{-1}{}^D - E_{-1}{}^H$, the isotope effect for the reverse reaction in step 1. Combination of (i) + (ii) gives $E_1{}^D - E_1{}^H$, which in turn can give $k_1{}^H/k_1{}^D$ from eq 1. The other two parameters are related to internal return: (iii) $E_{-1}{}^H - E_2$, the energy term, and (iv) A_2/A_{-1}, the preexponential term. Combining (ii) + (iii) gives $E_{-1}{}^D - E_2$.

Figure 1 contains seven simulated Arrhenius plots that were generated from eq 3. Three parameters were held constant and the fourth, $E_{-1}{}^H - E_2$, was allowed to vary from +10000 to −10000 cal mol^{-1}. The value used for $\Delta H_1{}^D - \Delta H_1{}^H$ was 46 cal mol^{-1},[15] $E_{-1}{}^D - E_{-1}{}^H$ was 1000 cal mol^{-1}, and A_2/A_{-1} was arbitrarily set at 1.0. In addition to generating the curves, k^H/k^D values were calculated for 10 °C intervals between 0 and 50 °C. These values were used to calculate the Arrhenius behavior predicted by eq 3 over a temperature range where many kinetic studies are conveniently carried out. The calculated values for $E_a{}^D - E_a{}^H$ and A^H/A^D are listed in Table II. To simulate k^D/k^T temperature dependence, we altered the first two parameters according to theory: $\Delta H_1{}^T - \Delta H_1{}^D = 20$ cal mol^{-1} and $E_{-1}{}^T - E_{-1}{}^D = 427$ cal mol^{-1}. The value of A_2/A_{-1} is independent of the isotope used, and $E_{-1}{}^D - E_2$ is 1000 cal mol^{-1} larger than $E_{-1}{}^H - E_2$. Using k^D/k^T and k^H/k^D values at 20 °C, a^L can be calculated for all three isotopes and these values are listed in Table II.[16a] Values for a^L can also be calculated directly by using eq 4 and these numbers are listed in parentheses next to values obtained by applying the Streitwieser treatment. The agreement between the two sets of values is remarkably good.

$$\frac{k_{-1}{}^L}{k_2} = \frac{A_{-1}}{A_2} \exp\left(\frac{E_2 - E_{-1}{}^L}{RT}\right) \tag{4}$$

Table III. Effects of Varying A_2/A_{-1} when Using Equation 3 to Simulate Temperature Dependence of k^H/k^D and k^D/k^T

$E_{-1}{}^H - E_2$,[a] cal mol^{-1}	A_2/A_{-1} [a]	k^H/k^D 20 °C	$E_a{}^D - E_a{}^H$,[b] cal mol^{-1}	A^H/A^D [b]	k^D/k^T 20 °C	y[c]
−2000	0.1	1.10	36	1.03	1.05	1.95
	1.0	1.24	−33	1.31	1.21	1.12
	10.0	2.29	−96	2.69	1.75	1.48
−1000	0.1	1.17	56	1.06	1.14	1.20
	1.0	1.83	214	1.27	1.59	1.30
	10.0	4.26	696	1.29	2.05	2.02
−500	0.1	1.28	169	0.96	1.25	1.11
	1.0	2.55	546	1.00	1.82	1.56
	10.0	5.08	931	1.03	2.11	2.18
0	0.1	1.53	389	0.79	1.44	1.17
	1.0	3.55	898	0.76	1.98	1.85
	10.0	5.57	1027	0.96	2.13	2.27
1000	0.1	2.85	1193	0.37	1.88	1.66
	1.0	5.27	1135	0.75	2.12	2.21
	10.0	5.94	1055	0.97	2.15	2.33
2000	0.1	4.82	1373	0.46	2.09	2.13
	1.0	5.87	1091	0.90	2.15	2.31
	10.0	6.01	1054	0.98	2.15	2.34

[a] Other parameters: $\Delta H_1{}^D - \Delta H_1{}^H = 46$; $\Delta H_1{}^T - \Delta H_1{}^D = 20$; $E_{-1}{}^T - E_{-1}{}^D = 427$. [b] The calculated k^H/k^D values between 0 and 50 °C at 10 °C intervals were used. [c] Defined for $k^H/k^D = (k^D/k^T)^y$.

Curve (a) simulates equilibrium isotope effects expected for a two-step mechanism when $k_{-1} \gg k_2$. At the other extreme, curve (g) depicts a case where k_1 is clearly rate limiting, $k_2 \gg k_{-1}$, and one observes the normal temperature dependence for a maximum possible primary kinetic isotope effect based on the energy values in the calculation. Curve (d) exhibits normal Arrhenius behavior with $\Delta E_a = 546$ cal mol^{-1}, $A^H/A^D = 1.0$, and $k^H/k^D = 2.55$ at 20 °C. If these values had been experimentally determined, they would most likely be interpreted as evidence for an asymmetric transition state having substantial zero-point energy differences between isotopically labeled compounds. Since these values were in fact generated by using eq 3, it becomes clear that such data cannot give a definitive answer regarding mechanism by making either a single temperature measurement or measurements over a considerable temperature range.[16b] To answer this mechanistic question, one must also measure the rate of reaction of the tritium-labeled compound at a single temperature. If $k^D/k^T = 1.51$ at 20 °C, the Swain–Schaad equation holds with $y = 2.26$; however, if $k^D/k^T > 1.65$, which requires $y = 1.87$, there is sufficient breakdown of the Swain–Schaad equation to suggest that an internal return mechanism may be the actual reaction pathway. The remaining curves all simulate anomalous Arrhenius behavior; however, deviations from normal behavior are small and, if such results were obtained from a kinetic study, the anomalous behavior would be attributed to experimental error.

Values listed in Table II were calculated by arbitrarily setting $A_2/A_{-1} = 1.0$ in order to investigate the variation of k^H/k^D with temperature resulting from changing the energy term of the internal return parameters. Greater deviations from normal Arrhenius behavior occur when the preexponential term, A_2/A_{-1}, is varied and examples of this are tabulated in Table III. When A_2/A_{-1} becomes greater than unity, curves like (b) and (c) become more pronounced and result in k^H/k^D values larger than expected from experimental ΔE_a values. With A_2/A_{-1} set at 10 and $E_{-1}{}^H - E_2$ at −2000 cal mol^{-1}, the value for k^H/k^D (2.29) appears to come from A^H/A^D (2.69) since ΔE_a is negative by 96 cal mol^{-1}. This is similar to experimental data we previously reported with temperature-independent isotope effects that appear to result from preexponential factors rather than from activation-energy differences. On the other hand, values for A_2/A_{-1} less than unity

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(14) $\Delta H_1{}^L = E_1{}^L - E_{-1}{}^L$.

(15) (a) $\Delta\Delta H_1$ was calculated from an average equilibrium isotope effect of 1.08 which we have observed in our isotopic exchange and dehydrofluorination reactions of $PhCLClCF_3$ and $PhCL(CF_3)_2$. (b) N. Bergman, *Acta Chem. Scand.*, **25**, 1517–1519 (1971), reports $K_H/K_D \sim 1.2$ in methanolic sodium methoxide for $PhCH_2CL(CH_3)CN$ at 60 °C.

(16) (a) Since a^H will always be the largest internal return ratio, we will normally report those values. (b) It should be noted that activation parameters obtained from the Arrhenius equation are always observed values. These values are not necessarily equal to the true parameters, especially in the case of a two-step mechanism where internal return can compete with the forward step. Curve (d) illustrates this point since the true ΔE_a is 1000 cal mol^{-1} while the value calculated from the Arrhenius equation is only 534 cal mol^{-1}.

Table IV

	case 20 °C	A_2/A_{-1}[a]	$E_{-1}^{H} - E_2$,[a] cal mol^{-1}	calcd ΔE_a, kcal mol^{-1}	calcd A^H/A^D
I	$k^H/k^D = 5.94$	10	1000	1.06	0.97
	$k^D/k^T = 2.15$	1.0	2330	1.08	0.93
	$a^H = 0.02$	0.1	3670	1.10	0.90
II	$k^H/k^D = 5.08$ $= (8.45)^b$	10	−500	0.93	1.03
	$k^D/k^T = 2.11$ $= (2.65)^b$	1.0	830	1.13	0.73
	$a^H = 0.24$	0.1	2170	1.34	0.51
		0.1	2170	1.69	0.46^b
III	$k^H/k^D = 4.25$ $= (6.91)^b$	10	−1000	0.70	1.29
	$k^D/k^T = 2.05$ $= (2.60)^b$	1.0	340	1.05	0.70
	$a^H = 0.56$	0.1	1670	1.40	0.38
		0.1	1670	1.79^b	0.32^b

[a] Other parameters: $\Delta H_1^{D} - \Delta H_1^{H} = 46$; $\Delta H_1^{T} - \Delta H_1^{D} = 20$; $E_{-1}^{D} - E_{-1}^{H} = 1000$; $E_{-1}^{T} - E_{-1}^{D} = 427$. [b] Parameters changed to $E_{-1}^{D} - E_{-1}^{H} = 1308$ and $E_{-1}^{T} - E_{-1}^{D} = 557$. All other parameters same as in footnote *a*.

Table V. Calculation of k^{35}/k^{37} Isotope Effects Using Equation 5

$E_{-1}^{H} - E_2$,[a] cal mol^{-1}	k^H/k^D[b] 25 °C	ΔE_a,[c] kcal mol^{-1}	A^H/A^D[c]	k^{35}/k^{37} at 25 °C: H compd	k^{35}/k^{37} at 25 °C: D compd
−10 000	1.08	0.0	1.0	1.013 60	1.013 60
0	1.93	0.7	0.6	1.012 36	1.006 94
400	2.61	1.1	0.4	1.011 36	1.004 71
800	3.67	1.5	0.3	1.009 81	1.002 89
1200	5.09	1.8	0.3	1.007 73	1.001 64
1600	6.64	1.8	0.3	1.005 46	1.000 89
1950	7.82	1.8	0.4	1.003 70	1.000 50

[a] $E_{-1}^{D} - E_{-1}^{H} = 1340$ cal mol^{-1}; $E_a^{37} - E_a^{35} = 8$ cal mol^{-1}; $A_2/A_{-1} = 0.1$. [b] k^H/k^D values calculated by using eq 3. [c] The calculated k^H/k^D values at 0, 25, and 50 °C were used.

cause curves like (e) and (f) to become pronounced and this results in k^H/k^D values smaller than those calculated from the corresponding ΔE_a values. With A_2/A_{-1} set at 0.1 and $E_{-1}^{H} - E_2$ at 2000 cal mol^{-1}, the value for k^H/k^D (4.82) is only 45% of the value predicted by the calculated ΔE_a of 1373 cal mol^{-1}. If this result were obtained experimentally, the small isotope effect would be inconsistent with the ΔE_a value and A^H/A^D (0.46) since they would suggest the necessity for a tunneling correction.

Although our treatment does not formally depend on the use of the Swain–Schaad equation, a single temperature study using all three hydrogen isotopes is still the most efficient method of detecting internal return. Lewis and Robinson[17] have evaluated the use of the Swain–Schaad relationship, $k^H/k^T = (k^H/k^D)^{1.442}$, and conclude that the unmodified equation can be quite good.[18] Streitwieser et al.[19] prefer to use 1.427 as the exponent, and normally use the rearranged form of the equation, $k^H/k^T = (k^D/k^T)^{3.344}$.[20] Since both tunneling and internal return have the largest effect on the protio compound, using k^D/k^T should give a better indication of what the expected k^H should be. If a tunneling correction is needed, one would expect that k^H_{obsd} would be significantly larger than that calculated from k^D/k^T. Conversely, if reaction proceeded with internal return, then k^H_{obsd} should be significantly smaller than that calculated from k^D/k^T. Albery and Knowles[21] recently warned that very accurate isotope effects are required to make use of deviations from a rather insensitive Swain–Schaad relationship to calculate amounts of internal return. A temperature-dependence study on all three isotopes therefore offers the potential of giving additional experimental reliability for the internal return process, and can also give information about the relative entropy and enthalpy relationship between the return step and the forward reaction. The use of eq 3 to simulate "experimental" results is not complicated by experimental error; however, one must keep in mind that actual experimental verification may be extremely difficult or impossible to obtain with the necessary accuracy in some cases.

Listed in Table IV are three cases where single-temperature isotope effects at 20 °C would suggest negligible to moderate amounts of internal return:[22] case I, $k^H/k^D = 5.94$, $k^D/k^T = 2.15$, and $a^H = 0.02$; case II, $k^H/k^D = 5.08$, $k^D/k^T = 2.11$, and $a^H = 0.24$; case III, $k^H/k^D = 4.25$, $k^D/k^T = 2.05$, and $a^H = 0.56$. In all three situations, the maximum value for k^H/k^D should be 6.02, ΔE_a should be 1.05 kcal mol^{-1} since these are the zero-point energies used in the calculations, and A^H/A^D should be 1.0. A_2/A_{-1} ratios were varied and $E_{-1}^{H} - E_2$ was adjusted accordingly to simulate the "experimental" results at 20 °C. Case I has a negligible amount of internal return and any further experimental studies could prove as inconclusive as the single-temperature measurements. If a 5% standard deviation is allowed for the isotope effects, the Swain–Schaad exponent would fall between 2.12 and 2.57 and the calculation of a^H could vary from 0.35 to −0.24.[23] Deviations from normal Arrhenius behavior are also small when A_2/A_{-1} is set at 10 or 1 for both case II and case III. Although deviations from the Swain–Schaad relationship are still small, they are more suggestive of an internal return mechanism, and a good temperature-dependence study could reinforce conclusions arrived at from single-temperature measurements.

When A_2/A_{-1} is 0.1, then both cases II and III should give clear-cut experimental results for anomalous Arrhenius behavior. ΔE_a values of 1.34 and 1.40 kcal mol^{-1} should result in k^H/k^D values of 10.0 and 11.2, respectively, at 20 °C. The "experimental" values of 5.08 and 4.25 are therefore much too low to be attributed to experimental error. This would also hold true for the A^H/A^D values of 0.51 and 0.38. The anomalous Arrhenius behavior would normally suggest the necessity for a quantum-mechanical tunneling correction, but the low k^H/k^D values would be inconsistent with this interpretation. Bell[24] gives a maximum zero-point energy difference for C–H vs. C–D bonds as 1354 cal mol^{-1} when allowance is made for bending vibrations. The "observed" ΔE_a values could therefore be considered normal, but not with the magnitude of the isotope effects. No explanation can be given for the low A^H/A^D values other than tunneling or the two-step mechanism with internal return. When we use Bell's maximum value for the zero-point energy differences, k^H/k^D becomes 8.45 (case II) and 6.91 (case III), and anticipated Arrhenius parameters follow: case II with $A_2/A_{-1} = 0.1$, $\Delta E_a = 1.69$ kcal mol^{-1}, and $A^H/A^D = 0.46$; case III with $A_2/A_{-1} = 0.1$, $\Delta E_a = 1.79$ kcal mol^{-1}, and $A^H/A^D = 0.32$. These results would certainly be interpreted as evidence for tunneling, but again the "normal" magnitude of the isotope effects would be puzzling.

Streitwieser et al.[25] report experimental results for the methanolic sodium methoxide catalyzed exchange at the 9 position of 9-phenylfluorene (9-PhFl) and 9-methylfluorene (9-MeFl) which give calculated internal return values similar to those of case III. Measurements of 9-PhFl at 25 °C give a calculated $k^H/k^D = 16.0$, $k^D/k^T = 2.50$, $a^T = 0.016$, and $a^H = 0.49$. Results for 9-MeFl are reported at 45 °C to yield $k^H/k^D = 11.9$, $k^D/k^T = 2.30$, $a^T = 0.024$, and $a^H = 0.59$. The small a^T values lead the authors to state "We conclude that internal return is not important for

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(17) E. S. Lewis and J. K. Robinson, *J. Am. Chem. Soc.*, **90**, 4337–4344 (1968).

(18) Discussion of this point starts on p 4338 of ref 17.

(19) A. Steitwieser, Jr., W. B. Hollyhead, A. H. Pudjaatmaka, P. H. Owens, T. L. Kruger, P. A. Rubenstein, R. A. MacQuarrie, M. L. Brokow, W. K. C. Chu, and H. M. Niemeyer, *J. Am. Chem. Soc.*, **93**, 5088–5096 (1971).

(20) Reference 19, p 5091.

(21) W. J. Albery and J. R. Knowles, *J. Am. Chem. Soc.*, **99**, 637–638 (1977).

(22) The term moderate return will always refer to the protio compound, since the corresponding deuterio or tritio compounds will have small to negligible amounts of internal return in these instances.

(23) Negative numbers for a^H arise when the apparent Swain–Schaad exponent is greater than 2.344.

(24) Reference 4, p 523.

(25) Reference 10, p 5099.

Table VI. Calculations Resulting from $A_i^{\mathrm{H}} \neq A_i^{\mathrm{D}}$

$(A_2/A_{-1})^{\mathrm{H}}$	$(A_2/A_{-1})^{\mathrm{D}}$	$k^{\mathrm{H}}/k^{\mathrm{D}}$ 25 °C	$E_{-1}^{\mathrm{H}} - E_2^{\mathrm{H}}$,[a] cal mol^{-1}	calcd ΔE_a, kcal mol^{-1}	calcd $A^{\mathrm{H}}/A^{\mathrm{D}}$	k^{35}/k^{37} at 25 °C H compd	k^{35}/k^{37} at 25 °C D compd
1.0	1.2	7.40	100	1.36	0.74	1.006 32	1.000 89
1.0	1.0	7.40	400	1.46	0.63	1.004 59	1.000 69
1.0	0.83	7.38	875	1.50	0.58	1.002 53	1.000 37
0.1	0.12	7.46	1475	1.87	0.32	1.006 16	1.000 89
0.1	0.10	7.44	1775	1.80	0.36	1.004 53	1.000 66
0.1	0.083	7.45	2275	1.65	0.46	1.002 41	1.000 35

[a] $E_1^{\mathrm{D}} - E_2^{\mathrm{D}}$ is set as 1354 cal mol^{-1} greater than $E_{-1}^{\mathrm{H}} - E_2^{\mathrm{H}}$; $\Delta H_1^{\mathrm{D}} - \Delta H_1^{\mathrm{H}} = 46$ cal mol^{-1}; $E_a^{37} - E_a^{35} = 8$ cal mol^{-1}.

the exchange of fluorenyl systems in methanolic NaOMe." In the context of their paper, the statement is certainly true; however, if one were interested in using primary kinetic isotope effects to describe a transition-state structure, the a^{H} values suggest that the observed $k^{\mathrm{H}}/k^{\mathrm{D}}$ values can be 30% lower than the true values for step 1 in Scheme I because of the moderate amount of internal return for the protio compound. In the paper preceding ref 10, Streitwieser et al.[19] report a temperature-dependence study of $k^{\mathrm{D}}/k^{\mathrm{T}}$ from 25 to 80 °C for fluorene-*9-d(t)* which gives $\Delta E_a^{\mathrm{T-D}} = 0.6$ kcal mol^{-1} and $A^{\mathrm{D}}/A^{\mathrm{T}} = 0.8$. These results can readily be interpreted as normal Arrhenius behavior, but this behavior is similar to the D/T results for case III(b) when $A_2/A_{-1} = 0.1$: $\Delta E_a^{\mathrm{T-D}} = 0.7$ and $A^{\mathrm{D}}/A^{\mathrm{T}} = 0.8$. When using eq 3 to simulate data, we have noticed that the amount of internal return increases with increasing temperature. This phenomenon has also been observed since the a^{H} value of 0.59 for 9-MeFl at 45 °C is slightly larger than that for 9-PhFl, 0.49, at 25 °C. At this point, one cannot conclude that there is internal return during the proton-transfer step from the 9 position of fluorenes to methoxide ion; however, one cannot rule out that possibility since the available data is consistent with moderate amounts of internal return in the protio compounds. A careful temperature-dependence study of the three isotopically labeled 9-PhFl-*9-L* or 9-MeFl-*9-L* could provide a definitive answer, but experimentally this would be a time-consuming undertaking and one must carefully consider if the additional information is necessary.

Listed in Table I are two examples of reactions which also have similar behavior to cases II or III. The ethoxide-promoted dehydrobrominations of $PhCH(CH_3)CH_2Br$[26a] and $PhCH_2CH_2Br$[27] both give $k^{\mathrm{H}}/k^{\mathrm{D}}$ values considered to be normal, but anomalous Arrhenius behavior which has been interpreted as evidence for tunneling. Since the accepted mechanism for these reactions is a concerted E2 pathway, one would not anticipate the possibility of internal return as with the Streitwieser data. In the case of $PhCH(CH_3)CH_2Br$, Shiner et al.[26] have reported excellent work on the temperature dependence of all three isotopes over a 50 °C range for H/D and a 40 °C range for D/T. Their data fit the current theories on tunneling and Bell has suggested an explanation for the possibility of observing "normal" $k^{\mathrm{H}}/k^{\mathrm{D}}$ values even when a tunneling correction is necessary. The suggestion is that an electronic coupling of the hydrogen with heavy-atom motions in the reaction coordinate can diminish the importance of that particular hydrogen motion and thus result in an isotopic zero-point energy change. This in turn can decrease the magnitude of the expected isotope effect. Therefore, the "normal" value is in actuality higher than it should be and is consistent with a tunneling interpretation.[28] Katz and Saunders have applied this to results obtained in β-elimination reactions.[29] When the Shiner data for all three isotopes is subjected to the Streitwieser treatment, one obtains moderate values of internal return which increase with temperature from $a^{\mathrm{H}} = 0.39$ at 25 °C to 0.54 at 65 °C. Equation 3 can simulate the data, Figure 2, using $E_{-1}^{\mathrm{H}} - E_2 = 1950$ cal mol^{-1} and $A_2/A_{-1} = 0.1$ for the internal return parameters and 1396 cal mol^{-1} for $E_1^{\mathrm{D}} - E_1^{\mathrm{H}}$ and 592 cal mol^{-1} for $E_1^{\mathrm{T}} - E_1^{\mathrm{D}}$ for zero-point energy differences.[30] On the basis of this fit alone, we would certainly be presumptuous to suggest that the mechanism of these dehydrobrominations was not E2; however, we do wish to point out that the primary kinetic isotope effect data are consistent with both the concerted single-step pathway and with a two-step mechanism that has a moderate amount of internal return.

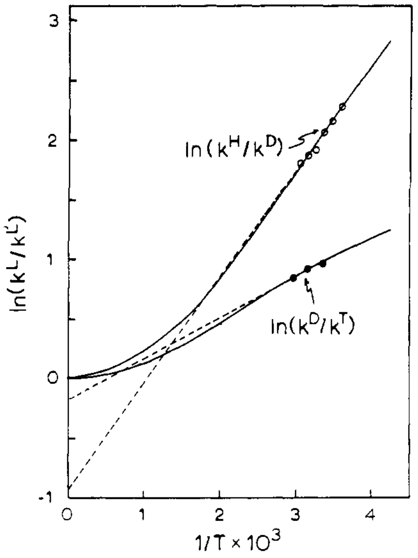

Figure 2. Solid lines represent the calculated ln $(k^{\mathrm{H}}_{\mathrm{obsd}}/k^{\mathrm{D}}_{\mathrm{obsd}})$ and ln $(k^{\mathrm{D}}_{\mathrm{obsd}}/k^{\mathrm{T}}_{\mathrm{obsd}})$ vs. $1/T$ for the elimination of $C_6H_5CLCH_3CH_2Br$ in EtOH/NaOEt. Parameters used: $A_2/A_{-1} = 0.1$; $\Delta H_1^{\mathrm{D}} - \Delta H_1^{\mathrm{H}} = 46$ cal/mol; $\Delta H_1^{\mathrm{D}} - \Delta H_1^{\mathrm{T}} = 20$ cal/mol; $E_{-1}^{\mathrm{H}} - E_2 = 1950$ cal/mol; $E_{-1}^{\mathrm{D}} - E_2 = 3290$ cal/mol; $E_{-1}^{\mathrm{T}} - E_2 = 3862$ cal/mol. Dashed lines represent the apparent ln $(k^{\mathrm{L}}_{\mathrm{obsd}}/k^{\mathrm{L'}}_{\mathrm{obsd}})$ as determined from the experimental isotope effects shown by ○ $(k^{\mathrm{H}}/k^{\mathrm{D}})$ and ● $(k^{\mathrm{D}}/k^{\mathrm{T}})$.

An elimination reaction does offer an additional method that could be used to determine if experimental data are consistent with a one-step or a two-step process. That would be the study of leaving group isotope effects,[31] and we will illustrate this using $^{35}\mathrm{Cl}/^{37}\mathrm{Cl}$ as an example. The anticipated magnitude of k^{35}/k^{37} rate ratios from a two-step dehydrochlorination, Scheme I, can be calculated by setting up an expression similar to eq 3:

$$\ln\left(\frac{k^{35}}{k^{37}}\right)_{\mathrm{obsd}} = \frac{E_2^{37} - E_2^{35}}{RT} + \ln\left[\frac{1 + (A_2/A_{-1})\exp((E_{-1}^{\mathrm{L}} - E_2^{37})/RT)}{1 + (A_2/A_{-1})\exp((E_{-1}^{\mathrm{L}} - E_2^{35})/RT)}\right] \quad (5)$$

Setting $E_2^{37} - E_2^{35} = 8$ cal mol^{-1} and arbitrarily using the same internal return parameters that gave the fit for the Shiner data

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(26) (a) V. J. Shiner, Jr., and M. C. Smith, *J. Am. Chem. Soc.*, **83**, 593–598 (1961); (b) V. J. Shiner, Jr., and B. Martin, *Pure Appl. Chem.*, **8**, 371–378 (1964).

(27) W. H. Saunders, Jr., and D. H. Edison, *J. Am. Chem. Soc.*, **82**, 138–142 (1960).

(28) A discussion of this with references is given by R. A. More O'Ferrall in ref 5, p 241.

(29) A. M. Katz and W. H. Saunders, Jr., *J. Am. Chem. Soc.*, **91**, 4469–4472 (1969).

(30) The values quoted as zero-point energy differences could arise from having residual zero-point energy in the transition state and therefore become Δ zero-point energy between H and D and D and T.

(31) An excellent review article regarding the use of various isotope effects has been written by A. Fry, *Chem. Soc. Rev.*, **1**, 163–210 (1972).

(for L = H, then $E_{-1}^{H} - E_2^{35} = 1950$ cal mol^{-1} and $A_2/A_{-1} = 0.1$), we calculate the value of k^{35}/k^{37} to be 1.003 70 at 25 °C for the protio compound. This value should be easily distinguished from the maximum value of 1.013 60 at 25 °C since the accuracy of ^{35}Cl/^{37}Cl measurements allows for calculation of k^{35}/k^{37} rate ratios to within 10–30 parts per 10^5.[33] If 1.003 70 had been experimentally obtained, the interpretation that such a small effect resulted from a partial C–Cl bond breaking in the transition state of an E2 mechanism would be quite reasonable.[32] Because the magnitude of the effect is consistent with both reaction pathways, it cannot give a definitive answer regarding the possible mechanism. Measurement of k^{35}/k^{37} for the deuterio compound as well could answer this question. The transition state for protio and deuterio compounds should be the same according to the Melander–Westheimer three-center model for isotope effects.[2,3] Therefore, the extent of hydrogen transfer and the amount of C–Cl bond breaking should be the same for protio and deuterio compounds, and this would result in the same observed k^{35}/k^{37} for each of the isotopically labeled compounds. For the two-step process, the deuterio compound has less internal return (L = D, then $E_{-1}^{D} - E_2^{35} = 3290$ cal mol^{-1} and $A_2/A_{-1} = 0.1$) and this results in the calculated k^{35}/k^{37} (from eq 5) dropping to 1.000 50 at 25 °C. Again the two values, 1.003 70 and 1.000 50, should be readily distinguished. Table V lists some predicted values of k^{35}/k^{37} resulting from the use of eq 5 for both protio and deuterio compounds by varying $E_{-1}^{L} - E_2$ and holding A_2/A_{-1} constant at 0.1. Measurement of a leaving-group isotope effect should also be able to distinguish a two-step process without internal return ($k_{-1} <<< k_2$) from an E2 mechanism since there should be no ^{35}Cl/^{37}Cl effect ($k^{35}/k^{37} = 1.000 00$) for the two-step mechanism. Thus these three types of elimination mechanisms should be subject to an experimental test of leaving-group isotope effects coupled with primary kinetic hydrogen isotope effects.

We have extended our experimental studies to include ethanolic ethoxide-promoted eliminations of $C_6H_5CL(CH_3)CH_2I$ and (I) and $C_6H_5CL(CH_3)CH_2Cl$,[34] and find that the calculated Arrhenius parameters are similar to those obtained by Shiner et al. for $C_6H_5CL(CH_3)CH_2Br$. Heavy-atom isotope effects measured for dehydroiodination of I, k^{12}/k^{14} for α carbon, and dehydrochlorination of II, k^{35}/k^{37}, are virtually the same for protio and deuterio compounds,[35] and this strongly supports the belief that these systems proceed by an E2 mechanism. The ethoxide-promoted dehydrochlorination of $C_6H_5CLClCH_2Cl$ has a different k^{35}/k^{37} value for protio and deuterio compounds, and this suggests that this system does not proceed by a simple concerted pathway.[35] Experimental results and mechanistic implications will be presented in future papers.

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Appendix

In response to the suggestion of one referee, we are including the form of eq 3 where $k_2^H \neq k_2^D$ and $A_i^H \neq A_i^D$:

$$\ln \frac{k^{H}_{obsd}}{k^{D}_{obsd}} = \left[\frac{(E_1^{D} - E_{-1}^{D}) - (E_1^{H} - E_{-1}^{H}) + E_2^{D} - E_2^{H}}{RT} \right] + \ln \frac{A_2^{H}}{A_2^{D}} + \ln \left[\frac{1 + (A_2^{D}/A_{-1}^{D}) \exp((E_{-1}^{D} - E_2^{D})/RT)}{1 + (A_2^{H}/A_{-1}^{H}) \exp((E_{-1}^{H} - E_2^{H})/RT)} \right] \qquad (6)$$

The value of the first term when using eq 3 originated from an experimentally determined equilibrium isotope effect[15] where $E_2^{H} \gg E_{-1}^{H}$. When using eq 6, this value would represent the first two terms and would include any contribution to the isotope effect from step 2. When $k_2^H \neq k_2^D$, the difference $(E_{-1}^{D} - E_2^{D}) - (E_{-1}^{H} - E_2^{H})$ will no longer equal $E_{-1}^{D} - E_{-1}^{H}$ since it now includes a ΔE_a for D–H in step 2. The calculated Arrhenius behavior will not be changed, but the two adjustable parameters will represent slightly different sets of energies. Table VI lists calculated isotope effects, Arrhenius parameters, and k^{35}/k^{37} when $A_i^H \neq A_i^D$ as well as when $A_i^H = A_i^D$. Also listed are the $E_{-1}^{H} - E_2$ necessary to make $k^H/k^D \sim 7.4$ at 25 °C for each pair of $(A_2/A_{-1})^L$ values. If one wishes to extend the treatment for a more precise analysis, eq 6 could be used; however, with the current state of the art, this would seem unwarranted. Even excellent Arrhenius studies would find it difficult to distinguish between the three pairs of $(A_2/A_{-1})^L$ sets for either case shown in Table VI. Kaldor and Saunders[36] have recently reported some excellent temperature-dependence studies on isotope effects which give Arrhenius parameters suggestive of tunneling despite k^H/k^D values which are in the normal to small range. They sugest that the contribution of heavy-atom motion to the motion along the reaction coordinate keeps the semiclassical isotope effects small, and therefore k^H/k^D values of the magnitude reported are not inconsistent with a tunneling correction. McLennan[37] has recently published some model calculations of isotope effects that can explain the "tunneling phenomenon" by postulating loose transition states for proton-transfer reactions. We feel that our interpretation is another alternative explanation and could help suggest experimental investigations that might ultimately help to analyze these mechanistic questions.

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(32) This type of interpretation has been made by several investigators regarding nitrogen and sulfur heavy-atom isotope effects and is reviewed in ref 31, pp 190–194.

(33) A Grout, D. J. McLennan, and I. H. Spackman, *J. Chem. Soc., Perkin Trans. 2*, 1758–1763 (1977).

(34) H. F. Koch, W. Tumas, and N. H. Koch, submitted for publication.

(35) H. F. Koch, J. G. Koch, W. Tumas, D. J. McLennan, B. Dobson, and G. Lodder, submitted for publication.

(36) S. B. Kaldor and W. H. Saunders, Jr., *J. Am. Chem. Soc.*, **101**, 7594–7599 (1979).

(37) D. J. McLennan, *Aust. J. Chem.*, **32**, 1883–1896 (1979).