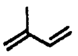
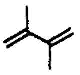
Table IV. Comparison of Calculated Addition Rate Constants (Column 4) for the Diphenylcarbenium Ion (**1-H,H**) with Experimental Values (Column 5)

compound	log k (CH_2Cl_2, −70 °C)	$\Delta S^{\ddagger}$,[a] J mol^{-1} K^{-1}	k(CH_2Cl_2, 24 °C), L mol^{-1} s^{-1}	k(($CH_2Cl)_2$, 24 °C),[b] L mol^{-1} s^{-1}
 **2a**	6.58	−116	5 × 10^6	9.5 × 10^6
	2.18	−139	2 × 10^3	<10^5
 **2d**	6.24	−108	4 × 10^6	7.1 × 10^6
	6.50	−108	7 × 10^6	2.7 × 10^7
	3.33	−108	4 × 10^4	<10^5

[a] Averaged value, of the reaction series for **2a** and **2d** (Table I), other values estimated from data in ref[5]. [b] Reference 27.

for **1-H,H**[13b] and the s and c values of Table II, one can calculate the rate constants log k (CH_2Cl_2, −70 °C) of **2a** and **2d**. From the reactivity ratios[5] (propene/**2a** = 4.03 × 10^{-5}, 2,3-dimethyl-1,3-butadiene/**2d** = 1.81, and 1,3-butadiene/**2d** = 1.24 × 10^{-3}) measured with respect to **1-OCH$_3$,H** one obtains the log k (CH_2Cl_2, −70 °C) values for the other compounds of Table IV. These numbers can now be converted into the rate constants at 24 °C, since $\Delta S^{\ddagger}$ can again be assumed to remain constant throughout a reaction series. Finally, considering that the reaction of **1-OCH$_3$,OCH$_3$** with 2-methyl-1-pentene was found to be 1.5 times faster in 1,2-dichloroethane than in dichloromethane, the agreement between the estimated rate constants in column 4 (Table IV) and those measured for radiolytically generated diphenylcarbenium ions by Dorfman[27] (Table IV, column 5) is better than expected. In view of the high sensitivity of the addition rate constants on the stabilization of the carbenium ions (eq 7), we expect the benzyl cation ($Ph{-}CH_2^+$) to be considerably more reactive than the benzhydryl cation. Therefore, we believe that the pulse radiolytically generated species, which reacts twice as fast with isobutene and 1,3-cyclohexadiene as Ph_2CH^+, cannot be the previously suggested parent benzyl cation.[27]

Conclusions

Ritchie type correlations, i.e. constant selectivity relationships are observed for reactions of diarylcarbenium ions with alkenes, if the substituents close to the reaction centers are kept constant. Under these conditions, the transition-state structure remains unaffected even if the reactivity is strongly altered by remote substituents. Substituent variations at the reaction center give rise to a variation of the transition-state structure, and linear free energy relationships with different slopes are observed.

Based on the rate constants and correlation equations presented in this and the preceding two articles, it has become possible to estimate rate constants for almost any diarylcarbenium ion with a large variety of alkenes. Since the correlations reported in this work have been found to hold also for the reactions of **1-X,Y** with allylsilanes, allylgermanes, allylstannes, and aromatic compounds, there is hope that a large body of carbenium ion nucleophile combinations can be described by a small set of kinetic parameters. Deviations from eqs 12–14, which may be encountered when the benzhydryl cations are replaced by other types of carbenium ions, require further examination.

Acknowledgment. We thank Dr. C. Schade for determining the rate constants of **2f,g** and the Deutsche Forschungsgemeinschaft for financial support.

Note Added in Proof. The discussion on negative activation enthalpies (Figures 9 and 10) was based on the constancy of $\Delta S^{\ddagger}$ during variation of the para-substituents in **1-X,Y**. A recent paper[28] suggests that this constancy may not hold for reactions with $\Delta H^{\ddagger} < 0$. Therefore, the high reactivity ratio (k_{2h}/k_{2r} = 44 toward **1-H,H**) might also reflect a change of the activation entropy, i.e., $\Delta S^{\ddagger}$ for the reaction **1-H,H** + **2h** may be less negative than for the other reactions of this series.

Supplementary Material Available: Tables of reaction conditions (concentrations) and rate constants of the individual kinetic runs and Eyring and Arrhenius parameters (14 pages). Ordering information is given on any current masthead page.

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(27) Wang, Y.; Dorfman, L. M. *Macromolecules* **1980**, *13*, 63.
(28) Scaiano, J. C.; Wintgens, V.; Haider, K.; Berson, J. A. *J. Am. Chem. Soc.* **1989**, *111*, 8732.

Tunneling in Elimination Reactions. Tests of Criteria for Tunneling Predicted by Model Calculations[1,2]

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Abstract: Isotope effects in E2 reactions of mixtures of $ArCL_2CH_2X$ and $ArCLTCH_2X$ (L = H or D) were determined by isotope fractionation methods. The temperature dependences of the secondary isotope effects, k^H_H/k^T_H (the subscript represents the transferred and the superscript represents the nontransferred atom) were abnormal as predicted by model calculations with tunneling when Ar = Ph and X = NMe_3 in EtO^-/EtOH (A_{aH}/A_{aT} = 0.705 ± 0.024) and when Ar = p-ClPh and X = OTs in t-BuO^-/t-BuOH (A_{aH}/A_{aT} = 0.704 ± 0.023). When Ar = Ph and X = Br in t-BuO^-/t-BuOH, the temperature dependence is not definitely abnormal (A_{aH}/A_{aT} = 0.927 ± 0.040), but the result can be shown still to be consistent with tunneling. The secondary effects k^D_D/k^T_D at 50 °C for Ar = Ph, X = NMe_3 in EtO^-/EtOH and Ar = p-ClPh, X = OTs in t-BuO^-/t-BuOH were 1.0314 ± 0.0099 and 1.0274 ± 0.0077, respectively, and remain well below the k^H_H/k^T_H values (1.2042 ± 0.0149 and 1.1907 ± 0.0122, respectively), when converted to k^H_H/k^T_H values by $k^H_H/k^T_H = (k^D_D/k^T_D)^{3.26}$, observations again diagnostic of tunneling. Efforts to apply the same criterion to primary isotope effects, k^D_D/k^D_T and k^H_H/k^H_T, were inconclusive.

The possibility of hydrogen tunneling in chemical reactions was recognized almost from the beginning of quantum theory.[5] General acceptance of the idea has been much slower in coming because of the difficulty in obtaining unequivocal experimental evidence. Most of the evidence is based upon primary hydrogen isotope effects, and only two criteria have been used with any degree of success.

Because the tunnel correction, Q_t, decreases with increasing mass, $Q_{tH} > Q_{tD} > Q_{tT}$, tunneling is expected to make k_H/k_D larger than it would otherwise be. Usually $k_H/k_D > 12$ and $k_H/k_T > 36$ at 25 °C can be taken as reasonably reliable evidence for tunneling.[6] Smaller isotope effects can, however, also contain contributions from tunneling. A more general criterion is an unusually steep temperature dependence for the primary isotope effect, such that the apparent activation energy difference, $E_{aD} - E_{aH}$ (or $E_{aT} - E_{aH}$), is larger than expected, and the ratio of apparent Arrhenius preexponential factors, A_{aH}/A_{AD} (or A_{aH}/A_{aT}), is substantially less than unity.[7,19] Numerous examples of bimolecular elimination reactions occur by this criterion with moderate tunneling.[8-11]

Another potential criterion of tunneling, deviation from the relationship between k_H/k_D and k_H/k_T derived with neglect of tunneling (eq 1)[12,13] has been disappointing. Lewis and Robinson

$$k_H/k_T = (k_H/k_D)^{1.44} \qquad (1)$$

report that eq 1 is obeyed for several reactions where other evidence strongly implicates tunneling.[14] They point out that tunneling must be extensive for the exponent to deviate significantly from 1.44. Model calculations also predict only small deviations due to tunneling at temperatures normally used for solution reactions.[15] We know of no experimental results where deviations from eq 1 are attributable to tunneling.

Recently we reported that secondary tritium isotope effects on proton abstraction from carbon often exceed the values expected from zero-point energy effects alone.[16] We suggested that these deviations might arise from tunneling and presented model calculations that supported this view.[17] The model calculations also made a number of other predictions. Tests of three of these predictions are reported in this paper: that the temperature dependence of the secondary isotope effect may be abnormally steep in the presence of tunneling, and that tunneling should cause measurable deviations from eq 2 (derivable from the same assumptions[13] as eq 1) for both secondary and primary isotope effects. Tunneling should cause greater deviations from eq 2 than from eq 1 because it contributes less to k_D/k_T than to k_H/k_D.

$$k_H/k_T = (k_D/k_T)^{3.26} \qquad (2)$$

The reaction system used in this investigation was the same as that in ref 16 (eqs 3–5). When L = H, $k_1/k_2 = k_H^H/k_T^H$ and $k_1/k_3 = k_H^H/k_H^T$; when L = D, $k_1/k_2 = k_D^D/k_T^D$ and $k_1/k_3 = k_D^D/k_D^T$.[18] The primary effect is determined experimentally from eq 6 and the secondary from eq 7, where R_0 is the initial molar activity of substrate, R^0_{ROL} is the molar activity of ROL at low fractions of reaction, and R_s^0 the molar activity of styrene at low fractions of reaction. The methods of determining these quantities

$$ArCL_2CH_2X + RO^- \xrightarrow{2k_1} ArCL{=}CH_2 + ROL + X^- \qquad (3)$$

$$ArCLTCH_2X + RO^- \xrightarrow{k_2} ArCL{=}CH_2 + ROT + X^- \qquad (4)$$

$$\xrightarrow{k_3} ArCT{=}CH_2 + ROL + X^- \qquad (5)$$

$$k_1/k_2 = 0.5R_0/R^0_{ROL} \qquad (6)$$

$$k_1/k_3 = 0.5R_0/R^0_s \qquad (7)$$

have been previously described[16] and will not be repeated here.

Secondary isotope effects were determined over a 40 °C temperature range for three reactions: (2-phenylethyl-*2-t*)trimethylammonium bromide (**1**) with sodium ethoxide in ethanol, 2-phenylethyl-*2-t* bromide (**2**) with potassium *tert*-butoxide in *tert*-butyl alcohol, and 2-(*p*-chlorophenyl)ethyl-*2-t* tosylate (**3**) with potassium *tert*-butoxide in *tert*-butyl alcohol. The isotope effects are reported in Table I and the Arrhenius parameters derived from them in Table II. The A_{aH}/A_{aT}[19] values for the reactions of **1** and **3** are unmistakably below unity and fully confirm the predictions of model calculations with tunneling.[17] For the reaction of **2**, however, A_{aH}/A_{aT} is not far enough below unity to demand tunneling, even though the magnitude of k_H/k_T (1.2705 ± 0.0099) is substantially above the maximum value predicted in the absence of tunneling (1.17[16]).

Table I. Temperature Dependence of Secondary Isotope Effects in E2 Reactions of *p*-$YC_6H_4CHTCH_2X$

Y,X	base/solvent	data pts, range[a]	Temp, °C[b]	k_H^H/k_H^T[c]
H,NMe_3	EtO^-/EtOH	5, 17–29	29.05	1.2163 ± 0.0031
H,NMe_3	EtO^-/EtOH	7, 12–36	40.30	1.1893 ± 0.0083
H,NMe_3	EtO^-/EtOH	8, 11–29	50.60	1.1647 ± 0.0092
H,NMe_3	EtO^-/EtOH	9, 5–38	64.78	1.1492 ± 0.0043
H,NMe_3	EtO^-/EtOH	9, 6–40	70.13	1.1376 ± 0.0028
H,Br	*t*-BuO^-/*t*-BuOH	9, 21–56	28.93	1.2893 ± 0.0150
H,Br	*t*-BuO^-/*t*-BuOH	9, 18–76	39.10	1.2826 ± 0.0103
H,Br	*t*-BuO^-/*t*-BuOH	9, 15–60	49.39	1.2705 ± 0.0099
H,Br	*t*-BuO^-/*t*-BuOH	10, 17–62	70.00	1.2402 ± 0.0103
Cl,OTs	*t*-BuO^-/*t*-BuOH	5, 21–49	29.50	1.2415 ± 0.0088
Cl,OTs	*t*-BuO^-/*t*-BuOH	6, 17–48	40.00	1.2172 ± 0.0024
Cl,OTs	*t*-BuO^-/*t*-BuOH	6, 25–49	50.00	1.1907 ± 0.0122
Cl,OTs	*t*-BuO^-/*t*-BuOH	6, 21–50	60.00	1.1809 ± 0.0059
Cl,OTs	*t*-BuO^-/*t*-BuOH	6, 18–44	70.00	1.1601 ± 0.0067

[a] Number of separate experiments and the range of percent completion of reaction they cover, respectively. [b] ±0.05 °C in most cases, ±0.1 °C in worst cases. [c] Rate of proton removal from unlabeled substrate divided by rate of proton removal from labeled substrate. Error limits reflect combined standard deviations of R_0 and R_p^0.

Table II. Arrhenius Parameters of Secondary Isotope Effects in E2 Reactions of *p*-$YC_6H_4CHTCH_2X$[a]

Y,X	base/solvent	$E_{aT} - E_{aH}$, kcal mol^{-1}	A_{aH}/A_{aT}
H,NMe_3	EtO^-/EtOH	0.326 ± 0.022	0.705 ± 0.024
H,Br	*t*-BuO^-/*t*-BuOH	0.200 ± 0.028	0.927 ± 0.040
Cl,OTs	*t*-BuO^-/*t*-BuOH	0.340 ± 0.021	0.704 ± 0.023

[a] Obtained by fitting the Arrhenius equation to data from Table I by the method of linear least squares. Error limits are standard deviations.

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(1) This work was supported by the National Science Foundation.

(2) Portions of this work were reported in preliminary communications, (see refs 3,4).

(3) Saunders, W. H., Jr.; Price, R. C.; Subramanian, R. In *Physical Organic Chemistry 1986*; Kobayashi, M., Ed.; Elsevier: Amsterdam, 1987; pp 197–202.

(4) Amin, M.; Price, R. C.; Saunders, W. H., Jr. *J. Am. Chem. Soc.* **1988**, *110*, 4085.

(5) Bell, R. P. *The Tunnel Effect in Chemistry*; Chapman and Hall: London and New York, 1980; Chapter 1.

(6) Melander, L.; Saunders, W. H., Jr. *Reaction Rates of Isotopic Molecules*; Wiley-Interscience: New York 1980; pp 140–143.

(7) Reference 6, pp 144–151.

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

(9) Kaldor, S. B.; Fredenburg, M. E.; Saunders, W. H., Jr. *J. Am. Chem. Soc.* **1980**, *102*, 6296–6299.

(10) Miller, D. J.; Saunders, W. H., Jr. *J. Org. Chem.* **1981**, *46*, 4247–4252.

(11) Miller, D. J.; Saunders, W. H., Jr. *J. Am. Chem. Soc.* **1979**, *101*, 6749–6750.

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

(13) Reference 6, pp 28–29, 143–144.

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

(15) Stern, M. J.; Weston, R. E., Jr. *J. Chem. Phys.* **1974**, *60*, 2815–2821.

(16) Subramanian, R.; Saunders, W. H., Jr. *J. Am. Chem. Soc.* **1984**, *106*, 7887–7890.

(17) Saunders, W. H., Jr. *J. Am. Chem. Soc.* **1985**, *107*, 164–169.

(18) The subscript to *k* indicates the atom that is transferred and the superscript the atom which remains behind. Thus k_L^L/k_T^L is a primary and k_L^L/k_L^T a secondary L/T effect.

(19) The subscript a denotes apparent Arrhenius parameters; these differ from the true values which would be found if a wide enough temperature range could be covered to reveal the curvature caused by tunneling.

Table III. Secondary H/T and D/T Isotope Effects in E2 Reactions of p-$YC_6H_4CLTCH_2X$ at 50 °C

Y,X	base/solvent	data pts, range[a]	L[b]	k_L^L/k_L^T[c]
H,NMe_3	EtO^-/EtOH	7, 14–45	H	1.2042 ± 0.0149
H,NMe_3	EtO^-/EtOH	6, 18–45	D	1.0314 ± 0.0099
Cl,OTs	t-BuO^-/t-BuOH	6, 25–49	H	1.1907 ± 0.0122
Cl,OTs	t-BuO^-/t-BuOH	6, 19–46	D	1.0274 ± 0.0077

[a] See footnote a, Table I. [b] Deuterated substrate (p-$YC_6H_4CDTCH_2X$ + p-$YC_6H_4CD_2CH_2X$) contains <2% H by NMR. [c] See footnote c, Table I.

To take up the predictions first,[17] a closer examination of the models lead to the conclusion that the Arrhenius parameters can still be nearly normal in the presence of significant tunneling. Consider, for example k_H^H/k_H^T and A_H^H/A_H^T for model 3 (Tables II and VI of ref 17). Even though approximately half of the effect is due to tunneling for n_{OH} (fraction of H transfer) = 0.3 and 0.5, A_H^H/A_H^T is above 0.9 in both cases. Examples numerically closer to the present experimental results are available from unpublished calculations. For example, a case where $k_H^H/k_H^T = 1.25$ and $(k_H^H/k_H^T)_{sc} = 1.08$[20] at 25 °C gives an A_H^H/A_H^T of 0.87.

Although the results on **2** can be shown to be not inconsistent with tunneling, there are reasons for greater confidence in the numbers from **1** and **3** than those from **2**. The k_H^H/k_H^T values for **2** in Table I are substantially larger than that reported earlier (1.071 ± 0.026).[16] Efforts to repeat the earlier value led to irreproducible results. The apparent source of the problem was found in a control experiment: bromine addition to a mixture of inactive styrene and 2-phenylethyl-*2-t* bromide in pentane gives styrene dibromide of appreciable activity. Evidently the unreacted 2-phenylethyl bromide that accompanies the styrene product from the elimination is suffering bromination at the 2-position, presumably by a free radical mechanism. This reaction could be suppressed in a more polar solvent, acetonitrile, in which the polar addition but not the radical substitution should be accelerated. While we have no reason to believe that the isotope effects on **2** in Table I are rendered unreliable by bromide substitution or other artifacts, it is prudent to keep in mind that a different and more complex workup procedure was needed for this reaction.

Some comment on the magnitudes of the k_H^H/k_H^T values in Table I is in order. Contrary to the previous report,[16] the value is now larger for **2** than for **1**. It is perhaps more logical to suppose that rehybridization in the transition state has proceeded farther for the relatively synchronous reaction of **2** than for the more E1cB-like reactions of **1** and **3**, so the order is not unexpected. A greater contribution from rehybridization for **2** would also help to explain why **2** gives a larger overall k_H^H/k_H^T but an apparently smaller tunnel correction than **1** or **3**.

Although a direct test of eq 2 using pure secondary or pure primary H/T and D/T isotope effects would be experimentally very difficult, an equivalent test can be accomplished as follows. If we repeat the experiments of eqs 3–5 with L = D, the resulting $k_1/k_3 = k_D^D/k_D^T$, and $k_1/k_2 = k_D^D/k_T^D$. It is a consequence of the rule of the geometric mean[21] that the two isotopically labeled atoms in a doubly labeled species should exert their effects independently. The isotope effect should be very close to the product of the isotope effects of the corresponding singly labeled species. But there should be no primary isotope effect in k_D^D/k_D^T because both transferred atoms are the same, and analogously there should be no secondary isotope effect in k_D^D/k_T^D. It should follow that

$$k_H^H/k_H^T = (k_D^D/k_D^T)^{3.26} \tag{8}$$

and

$$k_H^H/k_T^H = (k_D^D/k_T^D)^{3.26} \tag{9}$$

When eq 8 is applied to the k_D^D/k_D^T values in Table III, however, the calculated k_H^H/k_H^T values are 1.106 ± 0.033 and 1.092 ± 0.026 for **1** and **3**, respectively, both decisively below the directly measured values.

Other ways of viewing the same data lead to the same conclusion. If the exponent in eq 8 is taken as a disposable parameter, exponents of 6.00 and 6.47 are required to fit the experimental values on **1** and **3**. Similarly, Northrop's R values[22] (eq 10) are 1.92 and 2.08 for **1** and **3**, respectively. Though R values were originally intended to detect incomplete rate control by proton transfer, where $R < 1$ is expected, $R > 1$ is diagnostic of tunneling.[23]

$$R = \frac{k_H/k_T - 1}{(k_D/k_T)^{3.26} - 1} \tag{10}$$

The source of the observed deviations is qualitatively clear. Although the transferred D introduces no primary isotope effect due to zero-point energy differences into k_D^D/k_D^T, there is less tunneling when D is transferred than when H is. Consequently, the tunnel correction to the secondary isotope effect is attenuated relative to what it would be for k_H^D/k_H^T, if measurement of that quantity were feasible. These qualitative conclusions are supported by model calculations.[17] Calculated semiclassical (without tunneling) isotope effects obey eq 8 within ±1.1%, while the calculated full isotope effects deviate in the same way as the experimental ones.[29]

Deviations from eq 8 have recently been used to demonstrate that tunneling contributes to an enzymatic hydrogen transfer, the oxidation of benzyl alcohol to benzaldehyde by yeast alcohol dehydrogenase.[24] In that investigation, deviations from eq 9 by the primary isotope effects were also found. We turn now to our less successful efforts to test eq 9.

It should be mentioned first that failures of eqs 8–9 reflect two conceptually distinct, though usually linked, departures from "normal" behavior: tunneling, and violation of the rule of the geometric mean. Model calculations[17] predict that deviations from eqs 8 and 9 due to tunneling should usually be comparable and should be accompanied by violations of the rule of the geometric mean.[30] The one exception is model 1 of ref. 17, where tunneling contributes to the primary but not the secondary effect. This model differs from the others in not coupling bends of the nontransferred hydrogen to stretches of the transferred hydrogen. In this case there is no significant violation of the rule of the geometric mean by either the primary or secondary effects. In none of the models, however, was there a marked contribution of tunneling to the secondary effect without a concomitant contribution to the primary effect. The calculations show that semiclassical primary effects obey eq 9 within ±3.8%, but with tunneling k_H^H/k_T^H is 8–45% larger than $(k_D^D/k_T^D)^{3.26}$. If we assume that deviations from eq 9 should be comparable to those from eq 8 for our experimental results, as indicated by the calculations, about an 8–10% deviation is expected. This should in principle be experimentally detectable, though it is harder to determine the primary effects with high precision than the secondary.

Our initial figures on **1** forced the unexpected conclusion that $k_H^H/k_T^H < (K_D^D/k_T^D)^{3.26}$. The situation improved somewhat if, instead of using eq 6 and R_{ROL}^0 values determined at less than 5% reaction, we used the full equation governing this system of reactions, eq 11,[25] and greater fractions of reactions, F. While eq

$$\frac{R_{ROL}^0}{R_0} = \frac{k_1/k_3}{(k_1/k_2) + (k_1/k_3)}\frac{1}{F}[1 - (1 - F)^{[\{(k_1/k_2)+(k_1/k_3)\}/\{2(k_1/k_2)(k_1/k_3)\}]}] \tag{11}$$

11 cannot be solved explicitly for k_1/k_2, it can be solved iteratively if the measured values of k_1/k_3, F, R_{ROL}^0, and R_0 are inserted and k_1/k_2 varied until the equation is satisfied. By this method, k_D^D/k_T^D was smaller at high Fs than low. The most likely cause of such behavior is that the $ArCD_2CH_2X$ + $ArCDTCH_2X$ contained some

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(20) The subscript sc (semiclassical) denotes an isotope effect without the tunnel correction.

(21) Bigeleisen, J. *J. Chem. Phys.* **1955**, *23*, 2264–2267.

(22) Northrop, D. B. *Biochemistry* **1975**, *14*, 2644–2651.

(23) Northrop, D. B. Private communication.

(24) Cha, Y.; Murray, C. J.; Klinman, J. P. *Science* **1989**, *243*, 1325–1330.

(25) Reference 6, p 110.

Table IV. Primary H/T and D/T Isotope Effects in E2 Reactions of p-$YC_6H_4CLTCH_2X$ at 50 °C

Y,X	base/solvent	data pts, range [a]	L	k_L^L/k_T^L [b]
H,NMe_3	EtO^-/EtOH	5, 2–71	H	4.78 ± 0.09
H,NMe_3	EtO^-/EtOH	3, 5–63	D[c]	1.70 ± 0.03
Cl,OTs	t-BuO^-/t-BuOH	6, 3–87	H	13.87 ± 0.65
Cl,OTs	t-BuO^-/t-BuOH	6, 1–75	D[d]	2.28 ± 0.08

[a] Number of separate determinations of k_L^L/k_T^L and the range of percent completion of reaction they cover, respectively. See text for methods of calculation. [b] Rate of removal of L divided by rate of removal of T. Error limits are standard deviations. [c] Substrate contained 0.25% H by NMR. [d] Substrate contained 0.3% H by NMR.

protium, which would have little influence on the much smaller secondary effects, but could seriously increase the apparent primary effects. This error should be greatest at low fractions of reaction, where protiated species would make a disproportionate contribution to the total reaction. The higher F, the less this contribution should be. While both **1** and **3** contained <2% protium in the 2-position by high resolution ^1H NMR, this was enough to raise k_D^D/k_T^D by significantly more than experimental error.

To minimize this problem we used material depleted in protium. The precursor of **1**, $PhCD_2CH_2OTs + PhCDTCH_2OTs$, was allowed to react for 2 half-lives with potassium *tert*-butoxide in *tert*-butyl alcohol. The recovered tosylate contained ca. 0.25% β-H by ^1H NMR. Analogous treatment of p-$ClC_6H_4CD_2CH_2OTs$ + p-$ClC_6H_4CDTCH_2OTs$ gave recovered tosylate containing 0.3% β-H (^1H NMR). These materials were used to obtain the isotope effects reported in Table IV.

The k_D^D/k_T^D values for **1** and **3** were not significantly different whether eq 6 and $F < 0.05$ or eq 11 and $F > 0.05$ was used, so by this criterion protium contamination appears to have been reduced to a level that should no longer make k_D^D/k_T^D systematically larger than the true value. To ensure that the use of eqs 6 and 11 gave concordant results in the absence of this problem, both were used to determine k_H^H/k_T^H. No evidence for systematic dependence on F was found.

In spite of these precautions, $(k_D^D/k_T^D)^{3.26}$ is 5.64 for **1** and 14.68 for **3**, both apparently larger than the respective k_H^H/k_T^H values (4.78 and 13.87) by more than experimental uncertainty. The task in this case, however, is far more exacting than that for the secondary isotope effects. A value of k_D^D/k_T^D for **1** of 1.62, only 4.7% less than the measured value, would fit eq 9. A value only 10% less would give a clear deviation in the expected direction. Even smaller systematic errors could change the picture with **3**. A k_D^D/k_T^D of 2.24, less than 2% below the measured value, would fit eq 9, while a value 5% less than 2.28 would again give a clear deviation in the expected direction. We believe that such errors are not at all unlikely. First, the error limits quoted are standard deviations of the mean, so the probability of wider random errors is too great to be dismissed. Second, the method of measurement is more complex and more subject to systematic error for the primary than for the secondary isotope effect. Even the small amount of remaining protium in our depleted samples could still be affecting k_D^D/k_T^D and any error in the fraction of reaction also affects the molar activity. Neither of these sources of error is significant for the secondary effect.

It is obvious that unusually precise and accurate values of k_D^D/k_T^D and k_H^H/k_T^H are needed for definitive tests of eq 9. Our results cannot exclude deviations of the expected direction and magnitude from eq 9, given the possible sources of error. Since deviations in the expected direction were observed in enzymatic hydrogen transfers,[24] the predictions are clearly not discredited. It is obvious, however, that this criterion of tunneling is not likely to be generally useful, given its extreme sensitivity to isotopic impurities and systematic error.

Experimental Section

Solvents and Reagents. Ethanol was refluxed over magnesium and a catalytic amount of iodine for 12 h and distilled. *tert*-Butyl alcohol was refluxed for several hours over 3-Å molecular sieves (Union Carbide) and distilled. The alkoxide bases were obtained by dissolving the clean metal in the appropriate alcohol under nitrogen. Saturated solutions of potassium *tert*-butoxide were diluted to the desired concentration prior to use. Alkoxide concentrations were determined by titration with standard hydrochloric acid to the bromthymol blue end point.

(2-Phenylethyl-*2-t*)trimethylammonium bromide was prepared by the procedure of Subramanian and Saunders.[16]

(2-Phenylethyl-*2-t-2-d*)trimethylammonium bromide was prepared starting with ethyl phenylacetate-α,α-d_2 prepared by the method of Saunders and Edison,[26] except that the sodium salt of the phenyl malonic ester was treated with DTO (0.156 mCi mL^{-1}). The DTO was prepared by successive dilutions of 0.5 mL of HTO containing 500 mCi of tritium with 99.8% D_2O, which adds less than 0.02% H_2O to the D_2O. The ethyl phenylacetate-α-d-α-t had an activity of 2.8 mCi mol^{-1} and contained 1.2% β-H by high-resolution ^1H NMR spectroscopy. The quaternary ammonium salt obtained from this material was satisfactory for the secondary isotope effect determinations. For the primary isotope effect measurements (see Discussion), material of reduced protium content was obtained by treating 2-phenylethyl-*2-d-2-t* tosylate with 0.75 equiv of potassium *tert*-butoxide in *tert*-butyl alcohol until the base was consumed. Unreacted tosylate was recovered by dilution with water and extraction with ether. The ether extracts were washed with water, dried over sodium sulfate, and evaporated. The residue was crystallized from ether–petroleum ether. The recovered tosylate contained ca. 0.25% β-H (^1H NMR).

2-(*p*-Chlorophenyl)ethyl-*2-t* tosylate was prepared from p-chlorophenylacetic acid utilizing the sequence of reactions followed by Subramanian and Saunders[16] for 2-phenylethyl-*2-t* tosylate. The product had mp 80–81 °C (lit[27] mp 80–80.5 °C).

2-(*p*-Chlorophenyl)ethyl-*2-d-2-t* tosylate was prepared in the same manner as the *2-t* compound above starting with p-chlorophenylacetic-α-d-α-t acid, which was prepared as follows. Sodium metal (2 g, 0.087 mol) was dissolved in 20 mL of DTO (0.5 mCi mL^{-1}) under dry nitrogen and p-chlorophenylacetic acid (10 g, 0.058 mol) added. The mixture was refluxed with stirring for 3 days under dry nitrogen. The water was removed under vacuum and the residue dried for several hours under vacuum. It was dissolved in 20 mL of D_2O and refluxed three more days. The acid was regenerated as before[16] and found to contain 1.8% protium at the β-position (^1H NMR) and had an activity of 15 mCi mol^{-1}. This was converted in the usual way[16] to 2-(p-chlorophenyl)ethyl-2-d-2-t tosylate containing 1.8% β-H (^1H NMR). Treatment of a sample of this tosylate with 0.75 equiv of potassium *tert*-butoxide in *tert*-butyl alcohol (see above for procedure) gave recovered tosylate containing 0.3% β-H.

2-Phenylethyl-*2-t* bromide was prepared by the method of Subramanian and Saunders.[16]

Secondary Isotope Effects. (2-Phenylethyl-*2-t* or *2-d-2-t*)trimethylammonium bromide, ca. 1 g, was dissolved in 35–45 mL of dry ethanol in a 50-mL volumetric flask. Sodium ethoxide (0.1–0.5 M) was added to a 25-mL volumetric flask. Both flasks were equilibrated at least 1 h in a constant temperature bath held at ±0.05 °C of the stated temperature. Reaction was initiated by adding quickly by syringe 8–10 mL of base to the substrate solution and shaking vigorously. Two procedures were followed depending on the temperature. At low temperatures, an excess of base over substrate was used and the reaction stopped at a time calculated to give the desired fraction of reaction. At higher temperatures (ca. 50 °C and above), an insufficiency of base that would be consumed at the desired fraction of reaction was used and the reaction allowed to run overnight. In either case the reaction mixture was cooled to room temperature and 95% ethanol added to the mark. Four aliquots (usually 2 mL) of the solution were diluted with 95% ethanol in 50-mL volumetric flasks and the absorbance measured at 248 nm on a Varian DMS-200 spectrophotometer to determine the fraction of reaction. Allowance was made for the absorbance of unreacted starting material. The bulk of the reaction mixture was then added to ca. 100 mL of water (containing, for the low temperature reactions, sufficient hydrochloric acid to neutralize remaining base), and the resulting mixture was extracted with 3 × 25 mL portions of pentane or tetrachloromethane. The combined extracts were washed with 3 × 50 mL of water, dried over sodium sulfate or potassium carbonate, and filtered. Bromine (ca. 0.5 mL) was added to the filtrate. After 15 min the solution was evaporated under reduced pressure, and the residue was dissolved in 5 mL of ethanol. The ethanol solution was cooled to 0 °C and water added to precipitate the 1,2-dibromo-1-phenylethane. The dibromide was recrystallized twice from ethanol–water and sublimed in vacuo two or three times to give material of mp 73 °C (lit.[16] mp 74 °C). The original quaternary am-

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

(27) Banger, J.; Cockerill, A. F.; Davies, G. L. O. *J. Chem. Soc. B* **1971**, 498–502.

monium salt and the dibromide were counted to 0.2% precision on a liquid scintillation counter.

2-Phenylethyl-*2-t* bromide was dissolved in dry *tert*-butyl alcohol and treated with potassium *tert*-butoxide in *tert*-butyl alcohol in the same manner as for the quaternary ammonium salts. In all cases an insufficiency of base was used and the reaction allowed to proceed for at least 12 h. The workup was the same through extraction with pentane and drying. Instead of adding bromine, the pentane solution was evaporated under reduced pressure at ambient temperature and the residue taken up in 50 mL of acetonitrile. To the solution was added ca. 0.5 mL of bromine. After 10 min the solution was poured into 20 mL of a saturated aqueous solution of sodium bicarbonate and sodium sulfate. As soon as the color was discharged, 50 mL of saturated sodium chloride was added, and the mixture was extracted with 3 × 25 mL of tetrachloromethane. The combined extracts were dried over sodium sulfate, the solvent removed under reduced pressure, and the residue dissolved in ca. 3 mL of methanol and recrystallized at −78 °C. The recrystallization was repeated and the dibromide then sublimed twice (in vacuo).

2-(*p*-Chlorophenyl)ethyl-*2-t* or -*2-t-2-d* tosylate in dry *tert*-butyl alcohol was treated with potassium *tert*-butoxide in the same manner as for the quaternary ammonium salts. In all cases an insufficiency of base was used. The spectrophotometric analysis for the *p*-chlorostyrene was performed at 253 nm, where the molar absorbance is 1.95×10^4. The molar absorbance of the substrate (4.92×10^2) was accounted for in calculating the fraction of reaction. The workup was designed to remove as much as possible of the unreacted substrate so as to avoid contamination of the dibromide. The bulk of the reaction mixture was added to 100 mL of water and extracted with petroleum ether (bp 35–60 °C, 3 × 25 mL). The extracts were washed with 5 × 50 mL of water and dried over sodium sulfate, and the solvent was removed at reduced pressure and 25–30 °C on a rotary evaporator. To the residue was added 20 mL of ice-cold pentane and the solution decanted from the remaining unreacted substrate. Bromine (ca. 0.5 mL) was added to the pentane solution and after 15 min it was evaporated. The residue in 10 mL of petroleum ether was introduced into a short silica gel column and eluted with 75 mL of petroleum ether. The solvent was removed under reduced pressure, the residue was dissolved in 5 mL of ethanol, and water and ice were added to precipitate the dibromide. A solid formed upon scratching. It was filtered, dried, and sublimed three times in vacuo, mp 45–46 °C (lit[28] 43.7 °C).

Primary Isotope Effects. (2-Phenylethyl-*2-t* or -*2-d-2-t*)trimethylammonium bromide, 0.1–0.3 g, was dissolved in 5 mL of dry ethanol in a 25-mL volumetric flask. Sodium ethoxide [5 mL (the concentration was such as to give the desired fraction of reaction)] was added to a 10-mL flask. Both flasks were equilibrated for at least 1 h in a bath maintained at 50 ± 0.1 °C. A 0.5-mL aliquot of the base was added to the substrate solution by gas-tight syringe, the mixture shaken vigorously, and reaction allowed to proceed for 18–24 h. The reaction mixture was cooled to room temperature and diluted to the mark with dry ethanol. Aliquots were further diluted with 95% ethanol as in the determination of the secondary isotope effect above, and the absorbance of styrene at 248 nm was determined. The bulk of the reaction mixture was treated with a few drops of bromine and allowed to stand for several hours. The solution was distilled to obtain portions of pure ethanol for counting. In earlier experiments bulb-to-bulb distillation on a high vacuum line was used.[9] Better results were obtained by distillation at atmospheric pressure through a short Vigreux column. In either case, four 1.5–2-mL portions were collected and 1.0-mL aliquots counted to 2% precision.

2-(*p*-Chlorophenyl)ethyl-*2-t* or -*2-t-2-d* tosylate was dissolved in dry *tert*-butyl alcohol, equilibrated at 50 °C, and potassium *tert*-butoxide, also equilibrated, was added. The reaction was carried out just as for the quaternary ammonium salt, except that the reaction mixture was diluted with *tert*-butyl alcohol at the end, and aliquots for dilution with 95% ethanol were withdrawn before the mixture was removed from the bath. Absorbance at 253 nm was used to determine the fraction of reaction. Only distillation through a Vigreux column at atmospheric pressure was used to obtain samples of *tert*-butyl alcohol for counting.

Counting Procedures were the same as those utilized by Subramanian and Saunders[16] for the secondary isotope effects, and Kaldor, Fredenberg, and Saunders[9] for the primary isotope effects. In all cases a set of standard quenched samples was used to determine counting efficiency. Counting was done on a Beckman LS-100C or an LKB 1209 liquid scintillation counter.

Control Experiments. Erratic results were initially obtained on determination of the secondary isotope effect for 2-phenylethyl-*2-t* bromide under the conditions used for the quaternary ammonium salt. Bromination in pentane of a mixture of 2-phenylethyl-*2-t* bromide and inactive styrene gave styrene dibromide of appreciable activity. The same experiment utilizing the procedure described above for bromination in acetonitrile yielded inactive styrene dibromide, but the bromination and purification procedure must be followed closely to ensure this outcome.

When the quaternary ammonium salt or the tosylate were treated in their respective solvents in the absence of base for the time of the reaction, the distilled solvent was inactive. Thus, no solvolytic elimination occurs under the reaction conditions.

Distillation of ethanol-*O-t* or *tert*-butyl alcohol-*O-t* gave successive fractions with the same activity as each other and as the original solution, showing that no significant isotopic fraction occurs under the conditions of the distillation.

A solution of active styrene dibromide in ethanol was distilled as in the procedure for determining the primary isotope effect. The distillate was inactive. The analogous experiment with *p*-chlorostyrene dibromide, however, gave *tert*-butyl alcohol with significant activity in the bulb-to-bulb distillation. Distillation through a Vigreux column at atmospheric pressure yielded inactive *tert*-butyl alcohol.

A few drops of bromine were added to a solution of the radioactive tosylate in *tert*-butyl alcohol. The mixture was left overnight, and a few mL of the alcohol were distilled. The distillate was inactive.

Ethanol obtained by distillation from a reaction mixture was redistilled. The activity was unchanged, providing evidence that no active material other than the ethanol was being carried over by distillation.

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(28) Levi, L.; Nicholls, R. V. V. *Ind. Eng. Chem.* **1958**, *50*, 1005–1008.

(29) A referee asks whether weakening of bending motions without tunneling could cause the observed deviation. The model calculations already weaken the bending motions of the nontransferred hydrogen as much as possible without exceeding, for productlike models, the predicted $k^{\mathrm{H}}_{\mathrm{H}}/k^{\mathrm{T}}_{\mathrm{H}}$ of 1.17 for complete rehybridization of the C–H bond. Even a model which weakens the bends still further to give an unrealistically high $k^{\mathrm{H}}_{\mathrm{H}}/k^{\mathrm{T}}_{\mathrm{H}} = 1.44$ for a product-like transition state still gives a deviation of only 2.7%.

(30) A referee has pointed out that if the ratios $(k^{\mathrm{H}}_{\mathrm{H}}/k^{\mathrm{H}}_{\mathrm{D}})/(k^{\mathrm{D}}_{\mathrm{H}}/k^{\mathrm{D}}_{\mathrm{D}})$ and $(k^{\mathrm{H}}_{\mathrm{H}}/k^{\mathrm{D}}_{\mathrm{H}})/(k^{\mathrm{H}}_{\mathrm{D}}/k^{\mathrm{D}}_{\mathrm{D}})$ are used to measure deviations from the rule of the geometric mean for the primary and secondary isotope effects, respectively, the deviations must be equal by simple algebra. Our criteria, $(k^{\mathrm{H}}_{\mathrm{H}}/k^{\mathrm{H}}_{\mathrm{T}})/(k^{\mathrm{D}}_{\mathrm{D}}/k^{\mathrm{D}}_{\mathrm{T}})^{3.26}$ and $(k^{\mathrm{H}}_{\mathrm{H}}/k^{\mathrm{T}}_{\mathrm{H}})/(k^{\mathrm{D}}_{\mathrm{D}}/k^{\mathrm{T}}_{\mathrm{D}})^{3.26}$, are not required to be equal, but model calculations reveal no cases where the deviation is sizable for the secondary effect and negligible for the primary.