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Reaction of Crowded Olefins with Bromine. A Comparison of the Strained (*E*)-2,2,3,4,5,5-Hexamethylhex-3-ene with the Sterically Hindered Tetraisobutylethylene[†]

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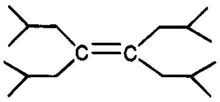
Abstract: (*E*)-2,2,3,4,5,5-Hexamethylhex-3-ene (HMH, **2**) reacts with Br_2 in chlorinated hydrocarbon solvents to give 3-bromo-2-*tert*-butyl-3,4,4-trimethylpentene (**4**), which is dehydrobrominated to 2,3-di-*tert*-butyl-1,3-butadiene (**5**). The first product of the interaction of the title olefin and Br_2 in 1,2-dichloroethane is a 1:1 CTC having $K_f = 84(0.3)\ M^{-1}$ at 25 °C, $\Delta H = -5.7(0.4)$ kcal mol^{-1}, and $\Delta S = -10.3(1.3)$ eu in this solvent. This probably evolves to a second CTC of 1:2 stoichiometry, which ionizes directly to a bromonium−tribromide ion pair. Removal of an H^+ from the bromonium ion by the counteranion gives the allylic bromide **4**. Kinetic investigations using **2**-H6 and its 3,4-bis(trideuteriomethyl) derivative **2**-D6 show a primary kinetic isotope effect $k_H/k_D = 2.17(0.25)$ at 25 °C, which decreases with increasing temperature, showing that the deprotonation step is at least partially rate determining. A similar conclusion holds for the reaction in acetic acid, where a $k_H/k_D = 2.05(0.1)$ at 25 °C is observed. This requires that the formation of the bromonium ion intermediate is a reversible process, as for the analogous reaction of tetraisobutylethylene (TIBE, **1**) with Br_2. The apparent activation energy for the reaction of **2**-H6 in acetic acid, $E_{a(obsd)} = 1.93(0.06)$ kcal mol^{-1}, is much lower than that for the reaction of TIBE (**1**), $E_{a(obsd)} = 15.65(1.22)$ kcal mol^{-1}. This is mainly attributable to steric strain present in the olefin HMH, **2**, which is relieved in the rate-determining transition state.

In spite of the very large amount of work carried out in the field of the electrophilic bromination of olefins,[1] continuing investigations[2] are bringing to light new mechanistic features which modify the traditional picture and introduce additional criteria for evaluating structure−reactivity relationships. Besides bromination studies in solution, the reaction of ethylene and halogen has also been studied in the gas phase recently.[3] Among recent findings, one of the most important is that the formation of bromonium ion intermediates during olefin bromination is not necessarily irreversible,[4] but a continuous spectrum of situations ranging from essentially irreversible ion formation to prevalent ion reversal appears to exist. This has important implications on the reactivity, since reversibility retards the observed rate of Br_2 consumption over what it would be in the absence of such.

Among the best-documented examples of reversible bromonium ion formation are cases of highly congested bromonium ions, where the product-forming step is made difficult by steric hindrance so that the return to reagents becomes competitive.[5,6] A clear-cut kinetic criterion for such reversibility, which can be applied when the crowded bromonium ion suffers a proton elimination instead of Br^- addition, is the measurement of a kinetic isotope effect (KIE) following the deuteration of the allylic positions of the olefin. Such a criterion has been successfully used[5] for the bromination of tetraisobutylethylene (TIBE, **1**), showing that a bromonium ion intermediate is reversibly formed from this hindered olefin.



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(*E*)-2,2,3,4,5,5-Hexamethylhex-3-ene (HMH, **2**) is a strained olefin which is reported[7] to react with Br_2 in CCl_4. As will be shown, in acetic acid the reactivity of this tetrasubstituted olefin

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[†] Dedicated to Professor Giancarlo Berti on the occasion of his 70th birthday.

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toward Br_2 is 4 orders of magnitude higher than that of tetraisobutylethylene. It was therefore of interest to establish if this much higher reactivity was due to the lack of reversal of the bromonium ion intermediate arising from HMH, **2**, or to some other feature of its reaction profile.

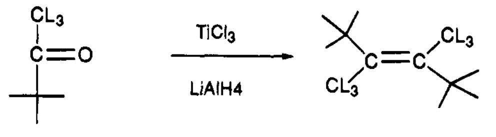
In order to check the reversibility, we subjected olefin **2**-H6 and its 3,4-bis(trideuteriomethyl) derivative **2**-D6 to the measurement of the bromination rate constants and apparent activation energies ($E_{a(obsd)}$) in acetic acid and in 1,2-dichloroethane (DCE). The $E_{a(obsd)}$ for the bromination of **1**, which had not been measured before, has also been determined for comparison purposes. The kinetics of **2**-H6 and **2**-D6 in both solvents at 25 °C gave a KIE ≥ 2, which is best rationalized in terms of a mechanism involving reversible bromonium ion formation.

Since, as will be shown, HMH, **2**, and TIBE, **1**, exhibited respectively a negative or very slightly positive value and a much higher positive value of $E_{a(obsd)}$ for bromination, the K_f and the thermodynamic parameters for the formation of a **2**$-Br_2$ CTC, the first product of the interaction of the olefin with the halogen and the precursor of the bromonium ion, have also been determined. A comparison of these thermodynamic parameters with the $E_{a(obsd)}$ for the overall reaction has given information about its mechanism and energy profile.

Results and Discussion

Products. (*E*)-2,2,3,4,5,5-Hexamethylhex-3-ene (**2**-H6) and its 3,4-bis(trideuteriomethyl) derivative (**2**-D6) have been prepared by McMurry coupling of methyl *tert*-butyl ketone[7] and trideuteriomethyl *tert*-butyl ketone units, respectively. The ^1H NMR spectrum indicated the presence of *ca.* 16% H at the allylic positions, on the basis of the intensities of the *tert*-butyl singlet at δ 1.15 and the five-line signal due to the HMH **2**-D5 product at δ 1.67.

Scheme 1



2-H6 : L = H
2-D6 : L = D

The direct ^1H NMR analysis of the reaction product obtained from 5×10^{-2} M **2**-H6 and Br_2 in dichloromethane-d_2 showed the disappearance of the *tert*-butyl (δ 1.14) and methyl (δ 1.73) signals of the olefin and the appearance of two new *tert*-butyl singlets at δ 0.93 and 1.05, the appearance of a methyl signal, broadened by long-range couplings, at δ 1.39, and the appearance of two vinyl signals, appearing respectively as a doublet (J = 0.7 Hz) and as a more complex multiplet due to long-range couplings, at δ 4.85 and 4.94. All these signals were consistent with the formation of the allylic bromide **4**. Furthermore, the spectrum showed a third *tert*-butyl singlet at δ 1.10 and an AB quartet at δ 4.70 and 5.09 (J = 1.5 Hz), indicating the presence of diene **5**. The ratio of **4** to **5** was about 8:2, based on NMR integration, and decreased with time. No other signals were present in the ^1H NMR spectrum, showing that, at variance with the previous report,[7] no vicinal dibromide was formed. The course of the reaction can therefore be represented as shown in Scheme 2, the allylic bromide being formed by removal of a proton by Br_3^- [8] from one methyl group of the bromonium ion and diene **5** being formed by subsequent dehydrobromination of the first-formed **4**. This confirms that sterically crowded ethylenes do not yield vicinal dibromides by bromination but react by addition/elimination, as already shown for **1**[5] and another cyclopentene derivative.[9]

Formation of a charge transfer complex between 2-H6 and Br_2. Compound **2** reacted much faster than **1** with Br_2 in 1,2-dichloroethane. In spite of this, the early stages of the reaction could be investigated by using a multichannel stopped-flow apparatus[10] having a mixing time ≤ 1 ms. A new absorption, showing its maximum around 272 nm and interpretable as a charge transfer band, immediately appeared when solutions of Br_2 and excess olefin were mixed in this instrument, monitoring in the wavelength range between 260 and 360 nm. The absorbances measured in this range immediately after mixing (A_0) increased, at constant [Br_2], with increasing olefin concentration, according to an asymptotic curve, indicating a progressive complexation of the halogen by the olefin to give a CTC (**3** in Scheme 2). An instantaneous progressive decrease in the visible Br_2 absorption band centered at 409 nm was simultaneously observed, monitoring the same reactions between 350 and 450 nm.

The initial absorbance−reagent concentration data measured at 25 °C and 330 nm, where the free halogen is at its absorption miminum (ϵ_{330} = 7.7 M^{-1} cm^{-1}) and gives practically no contribution to A_0, were fitted to the Scott equation for 1:1 complexes.[11] A satisfactory fit (r = 0.998) was obtained, giving K_f = 90 M^{-1} and $\epsilon_{330} = 3.5 \times 10^3$ M^{-1} cm^{-1} for the 1:1 CTC **3** at 25 °C. A similar, although less accurate, K_f value was also obtained by evaluating the concentration of the CTC, which does not absorb above 400 nm, from the instantaneous decrease in the free Br_2, observed at the visible absorption band of the halogen. This consistency assured that the A_0 values measured in the UV region and used in the Scott plot and in the nonlinear least-squares (NLLSQ) fitting discussed below were not affected by the first-formed products of the kinetic event.

Data of initial absorbance against reagent concentrations were also measured at 0 and 50 °C in order to determine the ΔH and ΔS for CTC formation. All the data taken at different wavelengths and temperatures were simultaneously fitted using a NLLSQ Fortran program, as previously described.[5] The ΔH and ΔS values and the K_f at the three temperatures, obtained by a fit of 130 data points taken in the 260−360 nm range, are reported in Table 1. The root mean square (rms) of the residuals of the fit was 0.04 absorbance unit. The molar extinction coefficient at the absorption maximum was $\epsilon_{272} = 2.3 \times 10^4$ M^{-1} cm^{-1}. The calculated spectrum of the 1:1 **2**-H6−Br_2 CTC is shown in Figure 1.

It is noteworthy that a comparison of the formation constants and thermodynamic parameters of Table 1 for the 1:1 **2**−Br_2 CTC with those reported for the **1**−Br_2 CTC (K_f = 9.71(0.19) M^{-1}, ΔH = −4.07(0.35) kcal mol^{-1}, ΔS = − 9.20(0.11) eu)[5] shows that the K_f of the former is about 1 order of magnitude higher than that of the latter and that this difference is essentially due to the enthalpy factor, the formation of the HMH−Br_2 CTC being more exothermic by *ca.* 1.6 kcal mol^{-1}. These data provide further confirmation that the olefin−Br_2 CTC formation constant is sensibly affected by the olefin structure, with the steric effects playing a significant role.

Kinetics of Bromination of 2-H6 and 2-D6. The rates of the reaction of **2** with Br_2 were first determined in 1,2-

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[8] In 1,2-dichloroethane the kinetics of olefin bromination are second order in Br_2 and the counteranion of the bromonium ion is a Br_3^-, whose dissociation constant to Br^- and Br_2 is $< 10^{-7}$ M.

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Scheme 2

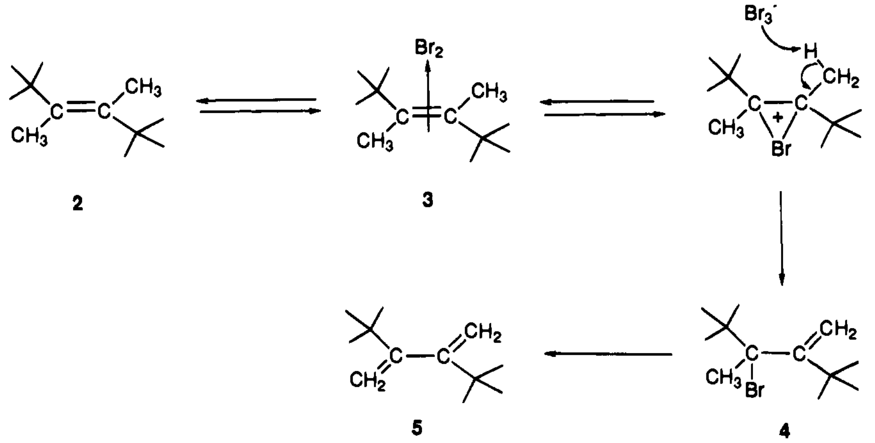

Table 1. K$_f$, ΔH, and ΔS Values for the **2**-H6–Br$_2$ CTC in the 0–50 °C Range

K_f (M^{-1})	T (°C)	ΔH (kcal mol^{-1})	ΔS (eu)
202(0.5)	0		
84(0.3)	25	−5.7 (0.4)	−10.3(1.3)
40(0.1)	50		

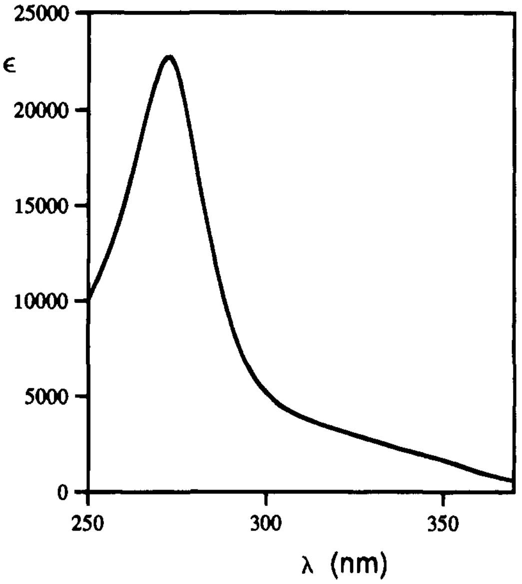

Figure 1. UV spectrum of the 1:1 **2**-H6–Br$_2$ CTC in DCE at 25 °C.

Table 2. Rate Constants for the Reaction of **2**-H6 and **2**-D6 with Br$_2$ in DCE and the Relative KIEs in the 6.5–70 °C Temperature Range

olefin	T (°C)	k_{3H} (M^{-2} s^{-1})	$k_{3D(obsd)}$ (M^{-2} s^{-1})	k_{3D} (M^{-2} s^{-1})	k_{3H}/k_{3D}
2-H6	6.5	7.5 (0.5) × 10^7			
2-H6	25	3.2(0.3) × 10^7			
2-H6	50	1.45(0.1) × 10^7			
2-H6	70	8.2(0.6) × 10^6			
2-D6	6.5		3.2(0.2) × 10^7	2.84 × 10^7	2.67(0.35)
2-D6	25		1.6(0.1) × 10^7	1.47 × 10^7	2.17(0.25)
2-D6	50		8.7(0.5) × 10^6	8.20 × 10^6	1.77(0.1)
2-D6	70		5.4(0.3) × 10^6	5.17 × 10^6	1.57(0.2)

dichloroethane, the solvent in which the **2**–Br$_2$ CTC had been investigated. The reagents were mixed in the stopped-flow apparatus, both at identical concentrations and with a large olefin excess, while the disappearance of the halogen at the visible absorption band was monitored. A third-order and pseudo-second-order rate law (eq 1) was obeyed up to over 90%

$$-\mathrm{d}[\mathrm{Br}_2]/\mathrm{d}t = k_3[\mathrm{Br}_2]^2[\mathrm{Ole}] \qquad (1)$$

conversion, as usually found for olefin bromination in low-polarity aprotic solvents.[4b–e,12–14] Hydrogen bromide was formed during the reactions, as shown by the above discussed product analysis (see Scheme 2), but under anhydrous conditions, this did not interfere with the unreacted free halogen to give tribromide species, whose formation from HBr and Br$_2$ in 1,2-dichloroethane is conditioned by the presence of traces of H$_2$O.[14]

The possibility that the reaction was photoinitiated because of the exposition of the cell to the whole radiation emitted by the tungsten lamp used as the source in the multichannel stopped-flow apparatus was checked by experiments carried out using a Durrum stopped-flow instrument in which the sample was reached only by a monochromatic 410 to 480 nm light beam. The same k_3 values, within the limits of the experimental error, were obtained for **2**-H6 in all cases. Furthermore, the reactions did not show any induction period and gave well-reproducible results in degassed and nondegassed solvent. All these data excluded the incursion of radical-based processes.

In order to determine the activation parameters, the kinetics were followed at four temperatures between 6.5 and 70 °C. The average third-order rate constants obtained for **2**-H6 and **2**-D6 at the four temperatures are reported in Table 2. Since the sample of **2**-D6 used for these measurements contained *ca.* 16% H, corresponding to 47% **2**-D5 and 53% **2**-D6, the kinetic constant observed for this sample, $k_{3D(obsd)}$, had to be corrected for the presence of the D5 compound in order to have the true rate constants for **2**-D6, k_{3D}. This correction was made on the basis of eq 2, assuming, as a first approximation, the absence

$$k_{3D(obsd)} = {}^{1}/_{6}(0.47k_{3H}) + {}^{5}/_{6}(0.47k_{3D}) + 0.53k_{3D} \qquad (2)$$

of significant secondary isotopic effects by D on the H$^+$ removal from the bromonium ion arising from **2**-D5. The corrected k_{3D} values are reported in Table 2, together with the corresponding KIEs at the four examined temperatures.

Rate constants and KIE had previously been determined[5] for the reaction of **1** with Br$_2$ in acetic acid at 25 °C. For comparison purposes, these quantities have therefore been measured for **2** between 25 and 75 °C in this low-polarity protic

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Table 3. Rate Constants for the Reaction of **1**-H8, **2**-H6, and **2**-D6 with Br_2 in Acetic Acid in the 25–70 °C Temperature Range and the Relative KIEs

olefin	T (°C)	k_{2H} ($M^{-1}s^{-1}$)	$k_{2D(obsd)}$ ($M^{-1}s^{-1}$)	k_{2D} ($M^{-1}s^{-1}$)	k_{2H}/k_{2D}
2-H6	25	$1.90(0.1) \times 10^4$			
2-H6	50	$2.40(0.15) \times 10^4$			
2-H6	70	$2.90(0.2) \times 10^4$			
2-D6	25		$1.00(0.05) \times 10^4$	9.20×10^3	2.05(0.1)
1-H8	25	0.76[a]			
1-H8	38	2.00(0.02)			
1-H8	50	5.90(0.03)			
1-D8	25			0.37[a]	2.3

[a] Taken from ref 5.

solvent, where the apparent activation parameters for **1**, not reported before, have also been determined. At the employed low Br_2 concentrations, the reactions in acetic acid cleanly obeyed up to at least 90% conversion the second-order (or pseudo-first-order, when working with a large olefin excess) rate law of eq 3, as usually observed in this protic solvent,[5,15]

$$-d[Br_2]/dt = k_2[Br_2][Ole] \tag{3}$$

where the ionization of the first-formed olefin–Br_2 CTC is electrophilically assisted by hydrogen bonding of the solvent to the developing bromide ion.[16] Again, the eliminated HBr did not interfere appreciably with the absorbance measurements through the formation of tribromide. In fact, the Br_3^- formation constant from HBr and Br_2 in anhydrous acetic acid is reported to be 1.25×10^2 M^{-1} at 25 °C.[17] On this basis, starting with 10^{-3} M Br_2, the Br_3^- present during the first 2 half-lives should have been always <10% of the unreacted Br_2. Radical-based processes were excluded also in this solvent on the basis of experiments of the type mentioned for the reactions carried out in DCE. The average second-order rate constants, k_{2H}, obtained for **2**-H6 and **1**, are reported in Table 3, which also includes the k_{2D}, obtained for **2**-D6, corrected through eq 2, and the previously determined k_{2D} for **1** at 25 °C, as well as the corresponding KIEs. At 25 °C, **2** had a k_2 2.5×10^4 times higher than **1**.

The data of Tables 2 and 3 show the occurrence of a KIE, k_H/k_D, of 2.17 and 2.05 for the reactions of **2** with Br_2 in DCE and in acetic acid at 25 °C, respectively. These values are strictly comparable to that of $k_H/k_D = 2.3$, obtained for the reaction of **1** with Br_2 in acetic acid at the same temperature.[5] It has been emphasized that KIEs of this magnitude are too large to be due to secondary β-effects of the allylic C-L bonds on a possible rate-limiting formation of bromonium ions. It can therefore be concluded that the KIE observed for the reaction of **2**, similar to that found for **1**, is essentially due to a primary isotopic effect in a transition state involving the rate-limiting or partially rate-limiting breaking of a C–L bond of the bromonium ion, with the counteranion acting as an internal base, leading to the allylic bromide **4**. The decrease in k_H/k_D with increasing temperature shown in Table 2 for the reaction in DCE is consistent with the prediction for a primary KIE.[18]

Arrhenius plots for the reactions of **2** and **1** with Br_2 in DCE and acetic acid, obtained using the data of Tables 2 and 3, are shown in Figures 2 and 3. The obtained apparent activation parameters are reported in Table 4. It must be remembered that these values are not to be considered as true activation parameters but as combinations of kinetic and thermodynamic quantities involved in multistep reactions.

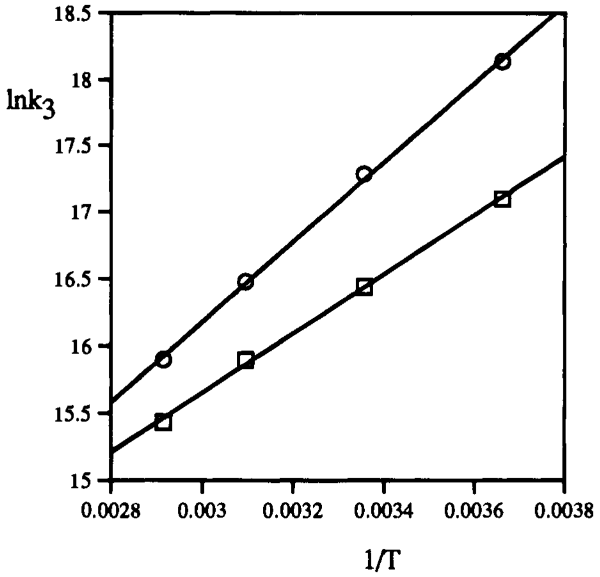

Figure 2. Arrhenius plots for the third-order reactions of **2**-H6 (○) and **2**-D6 (□) with Br_2 in DCE.

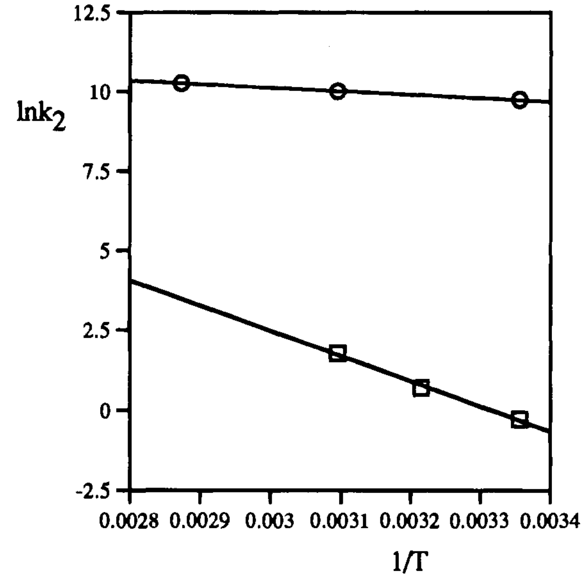

Figure 3. Arrhenius plots for the second-order reactions of **2**-H6 (○) and **1**-H8 (□) with Br_2 in acetic acid.

Table 4. Apparent Activation Parameters for the Reactions of **2**-H6, **2**-D6, and **1**-H8 with Br_2

olefin	solvent	$E_{a(obsd)}$ (kcal mol^{-1})	$\Delta H^{\neq}$ (kcal mol^{-1})	$\Delta S^{\neq}$ (eu)
2-H6	DCE	−6.60(0.23)	−7.20(0.25)	−48(1)
2-D6	DCE	−4.92(0.20)	−5.50(0.22)	−43(1)
2-H6	AcOH	1.93(0.06)	1.34(0.10)	−35(0.5)
1-H8	AcOH	15.65(1.22)	15.0(1.1)	−9(0.2)

Energy Profiles for the Bromination. The most striking result shown in Table 4 is the negative or very slighly positive $E_{a(obsd)}$ for the reaction of Br_2 with **2** respectively in DCE and in acetic acid, in constrast to the much larger positive value found for the **1** reaction in the latter solvent. It has been previously emphasized[14] that, for the reaction of an olefin and Br_2 involving a CTC as an essential intermediate, as that shown in Scheme 2, the apparent activation energy $E_{a(obsd)}$ is related

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to the CTC formation constant and enthalpy (K_f and ΔH) by eq 4, where $E_{a(2)}$ is the true activation energy for the transformation of the CTC into the product. It follows from eq 4 that, if $\Delta H < 0$, $E_{a(obsd)}$ can have a negative value, provided that $|\Delta H| >$

$$E_{a(obsd)} = E_{a(2)} + \Delta H\,(1/(1 + K_f[\mathrm{Ole}])) \qquad (4)$$

$E_{a(2)}$ and $K_f[\mathrm{Ole}] < |\Delta H|/E_{a(2)}$. The negative $E_{a(obsd)}$ obtained for the reaction of **2** in DCE is definite evidence for the involvement of CTCs on the reaction coordinate and represents the energy difference between the reactants and the highest rate-determining transition state, which lies below the reactants level.

The above discussed rationalization of the observed large KIE implies that this rate-determining transition state is one in which breaking of a C−L bond of the bromonium ion is occurring. The 1.7 kcal mol^{-1} difference in $E_{a(obsd)}$ for the reaction of **2**-H6 and **2**-D6 means therefore that the isotope-sensitive transition state is higher in energy by 1.7 kcal mol^{-1} when a D$^+$ in place of H$^+$ is lost. This is again consistent with the invoked primary kinetic isotope effect on the breaking of a C−L bond.

If we now introduce in eq 4 the $E_{a(obsd)}$, K_f, and ΔH values found for the reaction of HMH with Br_2 in DCE, we find again, for [HMH, **2**] = $(2-4) \times 10^{-3}$ M at 25 °C, a negative activation energy, $E_{a(2)} \cong -2$ kcal mol^{-1}. A similar result was obtained in an investigation of the bromination of cyclohexene in DCE[14] and was rationalized by assuming the exothermal formation, along the reaction coordinate, of a second spectroscopically undetectable olefin−Br_2 complex of 1:2 stoichiometry, having a formation enthalpy higher in absolute value than the true activation energy for its conversion to products. We believe that the above rationalization holds also for the present reaction of **2** with Br_2 in DCE, where the detected CTC **3** is transformed to an undetectable 1:2 complex (not shown in Scheme 2) from which the ionization to the bromonium ion actually occurs.

Even if the CTC formation constant between **2** and Br_2 in acetic acid has not been investigated, there is little doubt, also by analogy with the case of **1**, that 1:1 CTCs are involved as essential intermediates in this solvent, too. On the other hand, in acetic acid there is no need for **2**−Br_2 complexes of 1:2 stoichiometry since the 1:1 CTC can directly ionize to a bromonium−bromide ion pair with the electrophilic assistance of the protic solvent.[16] Therefore, the energy of the complex undergoing the ionization is not further decreased by association with a second Br_2 molecule, so that the rate-determining transition state may now be shifted to a higher level, comparable or higher than that of the reactants, with respect to the reaction in DCE. This can explain the slightly positive $E_{a(obsd)}$ found for the reaction of **2** with Br_2 in acetic acid.

The energy profile for this reaction can be qualitatively represented as shown in Figure 4.[19] It is clear from this figure that, since the barrier from the bromonium ion to the final product is higher than that for reversal to the CTC, the bromonium ion formation is actually reversible, as in the reaction of TIBE with Br_2.[5] The much higher reactivity of HMH relative to TIBE is therefore not due to lack of reversibility in the reaction of the former. It can also be observed that Figure 4 implies that the true activation energy of the reaction is composed of two terms relative to the CTC ionization and to the deprotonation of the cationic intermediate. The fact that the observed KIE is at the low end of the range expected for a primary effect ($1 < k_H/k_D < 9$)[20] is consistent with the overall barrier being a composite of an isotope-insensitive (or scarsely sensitive) barrier for the formation of the ionic intermediate and an isotope-sensitive one for the subsequent proton removal from it.

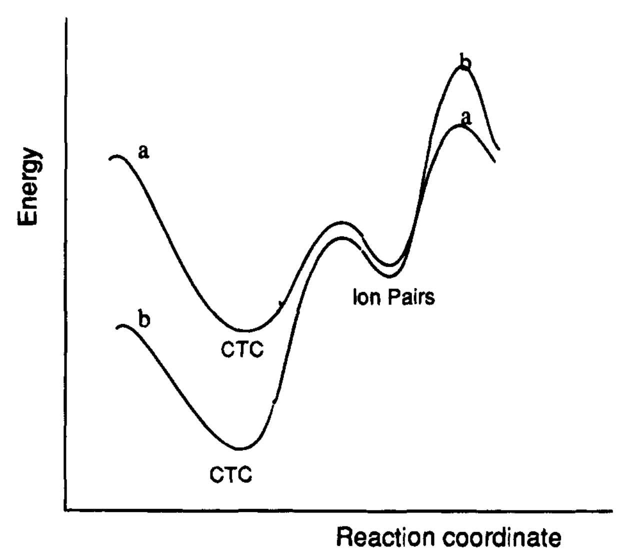

Figure 4. Qualitative energy profiles for reactions of HMH, **2**-H6 (a) and TIBE, **1**-H8 (b) with Br_2 in acetic acid.

The increased reactivity of **2** compared to **1** can be ascribed to an increase of strain energy of the former olefin. Using MM2 calculations,[21] the following values (in kcal mol^{-1}) have been obtained for **2**: $\Delta H^\circ_f = -35.74$, strain energy = 20.81.[22] Values found for **1** by the use of the same program are the following: $\Delta H^\circ_f = -83.00$, strain energy = 11.93.[23] Thus, **2** is more strained compared to **1** by *ca.* 9 kcal mol^{-1}. This amount reflects *ca.* 70% of the difference in $E_{a(obsd)}$ between the reaction of **1** and that of **2**, $\Delta E_{a(obsd)} \cong 13.5$ kcal mol^{-1}, and suggests that the very large increase in k_2 for the reaction of HMH over that of TIBE is mostly due to the higher steric strain present in the former olefin, which is relieved in the rate determining transition state. Such release in steric strain may accompany the ionization of the CTC, leading to the ionic intermediate if this species, which for simplicity is represented in Scheme 2 as a bromonium ion, has some bromocarbonium ion character.

Enhanced reactivity within a reaction series of sterically congested compounds can often be ascribed to ground state effects of the reactants.

Conclusions. The results of the present investigation confirm that the pre-equilibrium formation of olefin−Br_2 CTCs is a general phenomenon representing the first step of the interaction of the two reactants. A comparison of the presently found K_f for the 1:1 HMH−Br_2 CTC in DCE, 84 M^{-1} at 25 °C, with the few known values for other tetraalkyl-substituted olefins in the same solvent at the same temperature, **1** (9.71 M^{-1}),[5] adamantylideneadamantane (2.89×10^2 M^{-1})[24] and *d,l*-D_3-trishomocubylidene-D_3-trishomocubane (7.68×10^2 M^{-1}),[25] and with

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(19) It must be remarked that, while the relative positions of the reactants and of the transition states for the final deprotonation steps are defined by the $E_{a(obsd)}$ values, those of the ionic intermediates and of the associated transition states are not experimentally accessible. However, the similar KIE values found for **2** and **1** indicate that the ratios between the barriers from the CTC to the ionic intermediates and from the latter to the final products must be similar for each olefin. A consequence of this is that the energy levels of the two ionic intermediates should be not too different.

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(23) Previously reported values (kcal mol^{-1}) calculated by the MM2 force field: $\Delta H^\circ_f = -85.89$, strain energy = 10.72 (Andersen, L.; Berg, U.; Pettersson, I. *J. Org. Chem.* **1985**, *50*, 493).

the K_f previously found for a disubstituted olefin, cyclohexene ($0.47\ M^{-1}$),[14] gives further corroboration to the existence of sizable structural effects of both electronic and steric origin on the CTC formation.

The negative value of the apparent activation energy for the reaction of **2** in DCE ($E_{a(obsd)} = -6.6$ kcal mol^{-1}) and the very slightly positive value found in acetic acid ($E_{a(obsd)} = 1.93$ kcal mol^{-1}) are consistent with the involvement of the **2**$-Br_2$ CTCs along the reaction coordinate. In acetic acid, the 1:1 complex undergoes a direct solvent-assisted ionization, as shown also by the first-order dependence of the rate on both the olefin and Br_2, giving a bromonium (or bromocarbonium)$-$bromide ion pair, in which the anion can be stabilized by hydrogen bonding to the solvent. In DCE, a comparison of the thermodynamic parameters of the 1:1 **2**$-Br_2$ CTC with the $E_{a(obsd)}$ for the multistep reaction of the olefin and the halogen suggests a further exothermic association to give a second complex containing two Br_2 molecules, which ionizes to a bromonium (or bromocarbonium) ion paired to a tribromide anion stabilized by charge delocalization. This is consistent with the first-order dependence on the olefin and second-order dependence on Br_2 of the rate and is probably a general feature of the ionic mechanism of olefin bromination in low- or moderate-polarity aprotic solvents.

Kinetic investigations using **2**-H6 and **2**-D6, both in DCE and in acetic acid, have shown a large kinetic isotope effect, $k_H/k_D = 2.17$ (0.25) and 2.05 (0.10), respectively, which is best interpreted as an essentially primary effect in a rate-determining transition state involving the breaking of a C$-$L bond in a reversibly formed ionic intermediate and leading to an allylic bromide. The temperature dependence of this KIE and the 1.7 kcal mol^{-1} higher $E_{a(obsd)}$ for the reaction of **2**-D6 with respect to that of **2**-H6 are in agreement with this interpretation.

The much higher and positive $E_{a(obsd)}$ for the reaction in acetic acid of **1**, 15.65 kcal mol^{-1}, with respect to that of **2**, 1.93 kcal mol^{-1}, is not due to a lack of reversal of the intermediate ion pairs formed from the latter but seems rather to be related to a largely different ground state energy of the reactants due to steric strain, which can be released in the rate-determining transition state. Thus, strain effects can heavily affect the reaction rates of similarly tetrasubstituted olefins with Br_2. This is a further factor which must be taken into consideration in interpreting structure$-$reactivity relationships.

Experimental Section

Materials. (*E*)-2,2,3,4,5,5-Hexamethylhex-3-ene, **2**-H6, was prepared by McMurry coupling[26] of *tert*-butyl methyl ketone, as previously reported.[7] The product was purified by column chromatography on silica gel using hexane as the eluent. GL/MS: $m/e = 168$. ^{1}H NMR: δ 1.14 (s, C(CH)$_3$), 1.73 (s, $=$C$-$CH$_3$).

(*E*)-2,2,3,4,5,5-Hexamethylhex-3-ene-d_6, **2**-D6, was similarly obtained starting from *tert*-butyl methyl-d_3 ketone, which was prepared as follows: *tert*-butyl methyl ketone (9.2 g, 92 mmol) was refluxed in a mixture of 5 mL of ethanol-*d* (Aldrich, 99.5%), 45 mL of deuterium oxide (Aldrich, 99.8%), and 5 g of deuterium chloride (Aldrich, 37%) for 24 h. After cooling, the product was extracted with dichloromethane (3 × 30 mL). The organic phase was dried over Na_2SO_4 and filtered. After the solvent was evaporated, the product was distilled under normal pressure ($K_p \cong 108$ °C) to give 6.5 g of α-deuteriated ketone. This material was used in the McMurry coupling to give **2**-D6. ^{1}H NMR analysis indicated the presence of *ca.* 16% H at the allylic positions. Exact mass calcd for $C_{12}H_{18}D_6$: 174.2255. Found: 174.2250.

Tetraisobutylethylene (**1**) was prepared and purified as already reported.[5]

1,2-Dichoroethane (DCE, Fluka, puriss. p.a. ACS) was used as such without further purification. Commercial acetic acid (C. Erba, RPE) was purified before use as reported.[27] Bromine was withdrawn from 1-mL vials (C. Erba, RPE grade > 99.5%) opened immediately before use.

Product Study. Solutions of Br_2 and **2**-H6 (10^{-1} M) in dichloromethane-d_2 were rapidly mixed at room temperature, transferred into an NMR tube, and analyzed with a Brucker AC 200 instrument. Hydrogen bromide was immediately produced and the color of the halogen disappeared. The ^{1}H NMR spectrum, described in the Results and Discussion section, was consistent with the presence of the allylic bromide **4** and diene **5**[7] in an 85:15 ratio. The ^{13}C NMR spectrum showed the signals of the major component at 29.41 (C(CH$_3$)$_3$, 30.26 (C(CH$_3$)$_3$, 31.89 (CH$_3$), 43.53 (C$-$Br), 92.24 ($=$CH$_2$), 107.46 ($>$C$=$).

K_f measurements. For the measurements of K_f for the 1:1 **2**-H6$-Br_2$ CTC, DCE solutions containing Br_2 ($(2.0-4.0) \times 10^{-4}$ M) were rapidly mixed in a stopped-flow apparatus equipped with a diode-array detector[10] (mixing time $\leq$ 1 ms) with equal volumes of solutions of **2** ($(1-12) \times 10^{-2}$ M) in the same solvent at 0, 25, and 50 °C (±0.2), and the A_0 values were registered in the 260$-$360 nm interval. At least three independent determinations were carried out at each couple of reagent concentrations. Data obtained at 25 °C and 330 nm were used to fit the Scott equation. The composite data for all runs were fit by a previously described nonlinear least-squares procedure.[5] The experimental data for the fitting procedure were the analytical concentrations of both reagents, the optical path, the initial absorbances registered at 12 wavelengths (261, 270, 273, 279, 291, 300, 309, 321, 330, 339, 351, and 360), and the temperatures at which the spectrokinetics experiments were run (0, 25, and 50 °C). Fitting parameters were ΔH and ΔS for the formation of the olefin$-Br_2$ CTC, besides the molar absoptivity of the CTC at each examined wavelength. The obtained thermodynamic parameters are reported in Table 1, and the spectrum of the **2**-H6$-Br_2$ CTC is shown in Figure 1.

Kinetic Experiments. Kinetic experiments for the very fast reactions of **2**-H6 and **2**-D6 with Br_2 in DCE and in acetic acid and for the much slower one of **1** in acetic acid were run on the diode-array stopped-flow apparatus at the temperatures reported in Tables 2 and 3, while the visible absorption band of the halogen, centered at 410 nm in DCE and at 390 nm in acetic acid, was monitored. Temperature control was ensured by the mixing device of the apparatus, consisting of a SF-3L Hi-Tech support unit. In both solvents, kinetic constants were calculated at several wavelengths on the basis of the disappearance of the free bromine absorption band in the 350$-$450 nm interval. The same reactions were also carried out, for control purposes, on a monochannel Durrum stopped-flow instrument while they were monitored at a single wavelength between 410 and 480 nm.

Third-order (DCE) or second-order (acetic acid) kinetics were obtained when equal volumes of solutions containing identical concentrations ($(2-4) \times 10^{-3}$ M) of olefin and Br_2 were mixed. Pseudo-second- (DCE) and pseudo-first- (acetic acid) order kinetics were obtained by mixing 10^{-3} M Br_2 with a 10-fold excess of olefin. The experiments were repeated at least twice and accepted under the condition of a 5% maximum difference of the respective absorption/time curves. The third-order and second-order rate constants, obtained by fitting the absorption/time data registered at several wavelengths to the appropriate integrated rate equation, are reported in Tables 2 and 3, where the k_{3D} and k_{2D} values have been obtained by correcting the $k_{3D(obsd)}$ and $k_{2D(obsd)}$ as explained in the Results and Discussion section. The apparent activation parameters reported in Table 4 were obtained from the Arrhenius plots of Figures 2 and 3.

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