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Kinetic Evidence for Rate Determination during the Nucleophilic Step of Olefin Bromination. The Case of 5*H*-Dibenz[*b,f*]azepine-5-carbonyl Chloride

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The bromination of 5*H*-dibenz[*b,f*]azepine-5-carbonyl chloride has been investigated in 1,2-dichloroethane at 5, 25, and 50 °C. Working at reagent concentrations where the bromination was very slow, the formation of a 1:1 charge-transfer complex (CTC) was shown spectrophotometrically by the presence of a large difference absorption with respect to the olefin and to Br_2 alone. Although the formation constant of this CTC was too low ($K_f \leq 0.1\ M^{-1}$) to be determined, the products ($K_f\epsilon_{CT}$) at the three temperatures were obtained from the slopes of the linear plots of the difference absorbances against the olefin concentrations, and a value of the formation enthalpy, $\Delta H = -0.9\ (0.05)$ kcal mol^{-1}, was obtained from a plot of ln ($K_f\epsilon_{CT}$) against $1/T$. The kinetics of bromination were measured at variable temperature and reagent concentrations. At 50 °C and [Br_2] ranging between 2×10^{-2} and 5×10^{-1} M the usual third-order kinetics were observed. The same rate law was obeyed at 25 °C and [Br_2] $\leq 5 \times 10^{-2}$ M, whereas neither a third-order nor a fourth-order rate law was followed at 5×10^{-1} M Br_2 and olefin. At 5 °C and [Br_2] $\leq 5 \times 10^{-2}$ M the third-order rate law was again observed, but at 5×10^{-1} M Br_2 and olefin an overall fourth-order (third-order in Br_2) rate law was cleanly obeyed. A very small apparent activation energy, $E_{a(obsd)} = 3.45(0.1)$ kcal mol^{-1}, was found for the third-order process. A significant conductivity, which was highest at the lowest temperature, was found during the course of the reactions. *trans*-10,11-Dibromo-10,11-dihydro-5*H*-dibenz[*b,f*]azepine-5-carbonyl chloride was the only reaction product. It was shown by D NMR measurements to exist in 1,2-dichloroethane solution in two forms, both having anti-oriented bromine atoms and being nonequivalent because of different bond angles and bond lengths at C(10) and C(11). They are interconverted through a seven-membered ring inversion by torsion about the C(4a)–N(5)–C(5a) bonds, with a free activation energy $\Delta G^{\ddagger} = 16.6(0.2)$ kcal mol^{-1}. Introducing the values of $E_{a(obsd)}$ for the third-order bromination and of ΔH for the CTC formation in the equation $E_{a(obsd)} = E_a + \Delta H[1/(1 + K_f[Ol])]$ gives a true activation energy, E_a, too small for a reaction as slow as the investigated one. This shows that the rate-determining step of this reaction cannot be the CTC ionization, but is rather the collapse of bromonium–tribromide intermediates having a large and negative formation enthalpy. Low temperatures and high Br_2 concentrations favor the transformation of the tribromide counteranion into pentabromide, and the third-order dependence of the rate on Br_2 results from the fact that the rate-determining step involves a species containing three Br_2 and one olefin molecules. This shift from an overall third-order to a fourth-order rate law with decreasing temperature and increasing [Br_2] could provide a mechanistic criterium for rate determination during the nucleophilic step of olefin bromination.

In spite of the very extensive investigation devoted to the mechanism of electrophilic bromination of olefins[1] since the first postulation of bromonium ion intermediates by Roberts and Kimball,[2] the demonstration of the reversibility of their formation is surprisingly recent. Most studies dealing with this reversibility were based on product approaches that showed the exchange of Br^+ from solvolytically generated bromonium ions to scavenger olefins,[3] the formation of olefins at the expenses of dibromides from bromonium bromide ion pairs produced from bromohydrins and gaseus HBr,[4-6] or a cis–trans isomerization during the bromination of cis olefins.[4,7] A kinetic criterion for bromonium ion reversal consisting of the observation of a primary kinetic isotope effect by allylic C–D bonds on the bromination rate has recently been used,[8] but it can only be applied to particular olefins yielding substituted products by loss of a proton from the bromonium ion. Return of bromonium ions of highly congested olefins of the alkylideneadamantane type has also been deduced[9] from kinetic data on the basis of small kinetic solvent isotope effects associated with both small m_{Br}, obtained from Winstein–Grunwald mY_{Br} relationships, and *R*, defined as the rate ratios in two solvents of

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(4) Bellucci, G.; Chiappe, C.; Marioni, F. *J. Am. Chem. Soc.* **1987**, *109*, 515.

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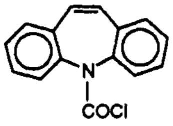
different nucleophilicity but similar ionizing power. Again, however, no dibromides are formed from these olefins.

It occurred to us that a more direct and general kinetic criterion to verify the reversibility of bromonium ion formation and the consequently implied rate determination during the product-forming (nucleophilic) step could consist in checking the consistence, for the proposed mechanism, of the rates and apparent activation energy for the bromination with the thermodynamic parameters of the involved reaction intermediates. Furthermore, if the rate-determining and the product-determining steps were coincident, the rate law would show a dependence on a power of the Br_2 concentration corresponding to the Br_2 content in the ionic intermediates, which can be bromonium–tribromide or bromonium–pentabromide species depending on the Br_2 concentration and the temperature.[10,11]

In order to check these possibilities, we chose to investigate the bromination of 5*H*-dibenz[*b,f*]azepine-5-carbonyl chloride (**1**), an olefin reacting smoothly with Br_2 to give only the expected dibromide (**2**) and whose bromonium ion had been independently shown to undergo easy reversal to olefin and Br_2.[5] The results have confirmed the anticipated change in rate law from overall third order to overall fourth order (third order in Br_2) with increasing Br_2 concentration and decreasing temperature. Furthermore, the determination of the apparent activation energy for the overall reaction and of the formation enthalpy of the first formed 1:1 **1**–Br_2 charge-transfer complex (CTC) has shown that the rate-determining step cannot be the CTC ionization but is rather the collapse of the ionic intermediates to **2**.



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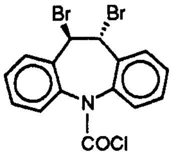

2

Results

Formation of a 1:1 Charge-Transfer Complex between 1 and Br₂. 5*H*-Dibenz[*b,f*]azepine-5-carbonyl chloride (**1**) reacted so slowly with bromine in 1,2-dichloroethane that the UV–vis spectra of solutions of these two reagents could be repeatedly registered with a conventional spectrophotometer at 5×10^{-3} M Br_2 and 5×10^{-2} to 5×10^{-1} M olefin, or at 10^{-1} M olefin and 5×10^{-3} to 5×10^{-2} M Br_2, without a significant olefin bromination occurring. As shown in Figure 1, under these conditions the spectrum of the solutions at 25 °C showed, beyond the olefin absorption region, a large difference absorption with respect to the olefin and to Br_2 alone. This difference absorption increased linearly, at constant 5×10^{-3} M Br_2, when the olefin concentration was gradually increased from 5×10^{-2} up to 5×10^{-1} M. A linear increase in this difference absorbance was likewise found when the olefin was kept constant at 0.1 M and the Br_2 concentration was increased from 5×10^{-3} up to 5×10^{-2} M. No decrease in the free Br_2 absorption, measured at 480–500 nm, was found in both sets of experiments even at the highest concentrations of the excess reagent. No significant conductivity was measured in any of these solutions. All these data showed that the observed difference absorption was not due to an ionic intermediate of the bromonium–tribromide type, which would have exhibited a measurable conductivity, but was rather attributable to a molecular 1:1 charge-transfer complex (CTC) that was in equilibrium with the reagents at a concentration not exceeding *ca.* 5% of that of the total Br_2 and whose absorption maximum was buried under the large olefin band. Similar CTCs, with λ_{max} occurring in the 240–340 nm range, have been reported for aliphatic olefins in halogenated hydrocarbon solvents.[12,13] In particular, λ_{max} values around 315–330 nm have been reported for phenyl-substituted olefins like styrene and β-methylstyrene in CCl_4[13] and Freon-113.[12]

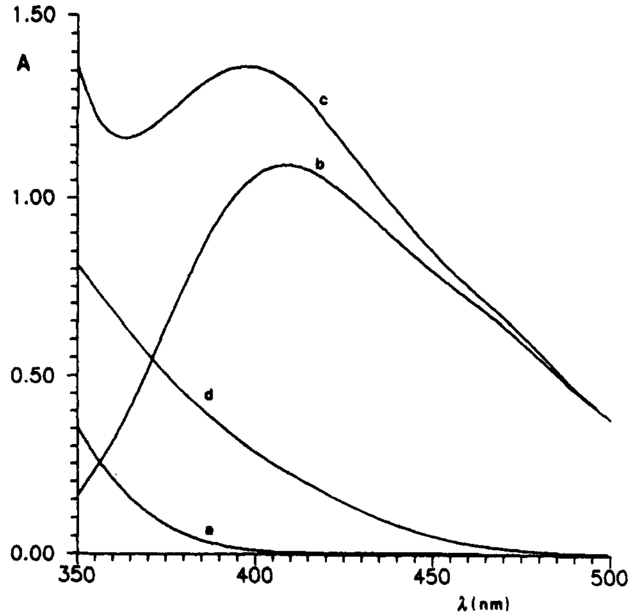

Figure 1. UV–vis spectra of 5×10^{-1} M **1** (a), 5×10^{-3} M Br_2 (b), and 5×10^{-1} M **1** and 5×10^{-3} M Br_2 (c), in 1,2-dichloroethane at 25 °C, and the difference between c and a + b, d.

A quite low value of the formation constant of this CTC, $K_f \leq 0.1$ M^{-1}, could be inferred from the linearity of the plots of the difference absorbance against the concentration of the excess reagent (see Figure 2) and from the concomitant lack of a significant decrease in the Br_2 absorption above 480 nm (see Figure 1). Unfortunately, it was not possible to determine the individual values of K_f and of the molar extinction coefficient, ϵ_{CT}, of this CTC on the basis of the available data because of the too low extent of complexation.[14] However, the product ($K_f\epsilon_{CT}$) could be simply obtained from the slope of the straight line obtained by plotting the difference absorbances as a function of the olefin concentration at constant [Br_2] according to eq 1, where l is the optical path, $[Br_2]_{free} \cong$

$$\Delta A/l = K_f\epsilon_{CT}[Br_2]_{free}[Ol] \qquad (1)$$

$$\ln (K_f\epsilon_{CT}) = \Delta H/RT - \Delta S/R + \ln \epsilon_{CT} \qquad (2)$$

$[Br_2]_{tot}$, and the olefin is in large excess. Figure 2 shows these plots obtained for 5.2×10^{-3} M Br_2 and 5×10^{-2} to

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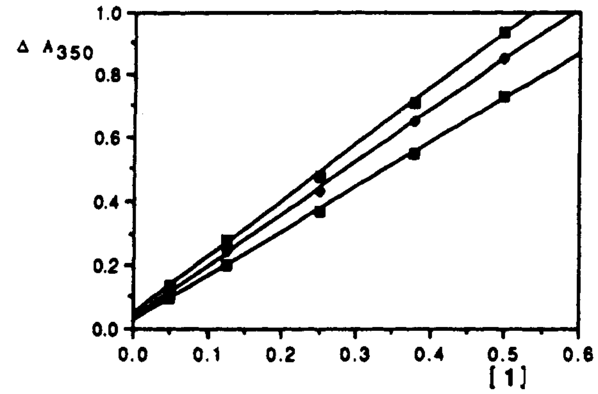

Figure 2. Plots of the difference absorbance at 350 nm against the olefin concentration for 5.2×10^{-3} M Br_2 and 5×10^{-2} to 5×10^{-1} M 1 in 1,2-dichloroethane at 5 (▣), 25 (◆), and 50 °C (■).

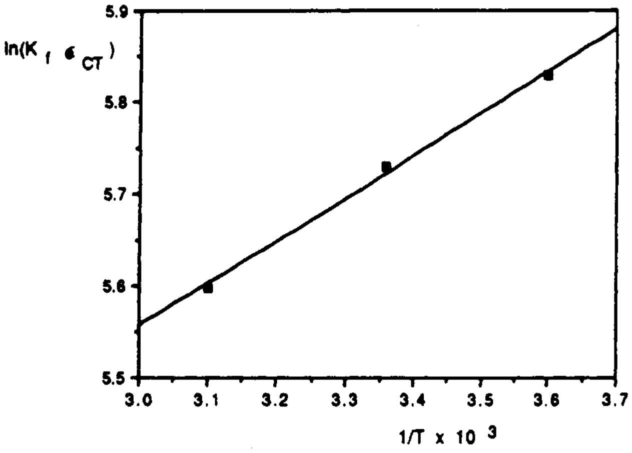

Figure 3. Fit of the $K_f\epsilon_{CT}$ products obtained in 1,2-dichloroethane at 5, 25, and 50 °C to eq 2.

5×10^{-1} M olefin at 5, 25, and 50 °C. The respective values of the products ($K_f\epsilon_{CT}$), 338 (20), 314 (15), and 268 (15) M^{-2} cm^{-1}, showed a decrease in K_f with increasing temperature, clearly indicating that, as expected, the formation of the complex was exothermal. These data were then used to calculate the formation enthalpy of the CTC by a plot of ln (K_f ϵ_{CT}) against $1/T$, according to eq 2. This required that ϵ_{CT} be constant in the investigated temperature interval, an assumption that had been considered quite unjustifiable before.[15] We have previously shown,[16] however, that ϵ_{CT} for the 1:1 cyclohexene–Br_2 CTC is actually temperature independent, within the limits of the experimental error, in the 15–35 °C temperature range, and cannot see any reason why the present CT absorption should behave differently. We therefore believe that the formation enthalpy of this CTC can be obtained by eq 2 with fair confidence. Figure 3 shows a plot of ln($K_f\epsilon_{CT}$) against $1/T$ from the slope of which a $\Delta H = -0.9$ (0.05) kcal mol^{-1} is obtained. When compared with the analogous thermodynamic data obtained[16] for the CTC of a simple alicyclic olefin like cyclohexene, $K_f = 0.47$ M^{-1} at 25 °C and $\Delta H = -4.60$ kcal mol^{-1}, the present data show that the conjugation of the carbon–carbon double bond with the two aryl groups markedly decreases both the formation constant and the formation enthalpy of the CTC. This is further evidence for the dependence of the thermodynamic parameters of olefin–Br_2 CTCs on the olefin structure.[17]

Kinetics of Bromination of 1. The kinetics of bromination of 1 were measured spectrophotometrically in 1,2-dichloroethane monitoring the disappearance of Br_2 at 480–540 nm, where neither the CTC or eventual ionic intermediates of the bromonium–polybromide type absorbed. A large olefin excess was used when the Br_2 concentration was relatively low ($\leq 5 \times 10^{-2}$ M) in order to have a reasonable reaction rate, while a 1:1 ratio of the two reagents was used at higher Br_2 concentrations. The reactions were carried out at 5, 25, and 50 °C.

At 50 °C the reaction always followed the usual third-order rate law of eq 3, whose integrated form for excess

$$-d[Br_2]/dt = k_3[Ol][Br_2]^2 \qquad (3)$$

$$1/C - 1/C_0 = k_{pseudo\text{-}2}[Ol]t \qquad (4)$$

$$1/C^2 - 1/C_0^{\,2} = 2k_3t \qquad (5)$$

$$-d[Br_2]/dt = k_4[Ol][Br_2]^3 \qquad (6)$$

$$1/C^3 - 1/C_0^{\,3} = 3k_4t \qquad (7)$$

$$1/C^{2.5} = kt + \text{constant} \qquad (8)$$

olefin concentrations (pseudo-second-order conditions) is given by eq 4 and for identical initial reagent concentrations (C_0) is given by eq 5. An average $k_3 = 2.15 \times 10^{-2}$ M^{-2} s^{-1} was found working under both third-order and pseudo-second-order conditions, at initial Br_2 concentrations ranging between 2×10^{-2} and 5×10^{-1} M. A $k_3 = 1.9(0.1) \times 10^{-2}$ M^{-2} s^{-1} at 50 °C had been reported before for reactions carried out at 0.2 M Br_2 and 1.[5]

The same rate law was obeyed by reactions performed at 25 °C when the initial Br_2 concentration was $\leq 5 \times 10^{-2}$ M and the olefin was in a 10-fold excess. However, when the Br_2 concentration was increased more and more marked deviations from this rate law became apparent. At initial 5×10^{-1} M Br_2 and 1 neither eq 5 nor eq 7, the integrated form of the fourth-order rate law (6) for equal olefin and Br_2 concentrations, was satisfactorily obeyed. A fit to eq 8 gave instead an excellent straight line ($r = 1$), suggesting something intermediate between third- and fourth-order kinetics. Figure 4 shows the fits of the absorbance/time data of this reaction to eqs 5, 7, and 8.

The reactions carried out at 5 °C with initial Br_2 concentrations $\leq 5 \times 10^{-2}$ M and a large excess of 1 again obeyed cleanly the integrated rate equation (4), but when the halogen concentration was increased 10-fold and a 1:1 ratio of the reagents was used the integrated third-order rate equation (5) was not followed (Figure 5). In this case, however, an excellent fit ($r = 1$) of the absorbance/time data to eq 7 was found for more than 2 half-lives, as shown in Figure 5.

The third- and fourth-order kinetic constants obtained at the different reagent concentrations and at the three examined temperatures are summarized in Table I. The data show that at Br_2 $\leq 5 \times 10^{-2}$ M all reactions obeyed the usual third-order rate law all over the 5–50 °C range.

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[16] Bellucci, G.; Bianchini, R.; Ambrosetti, R. *J. Am. Chem. Soc.* **1985**, *107*, 2464.

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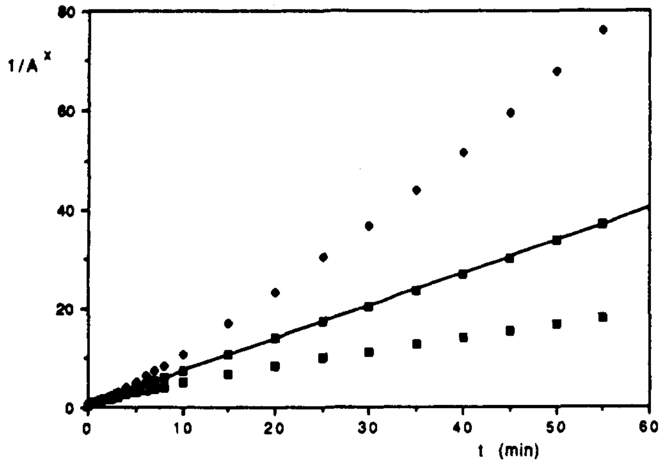

Figure 4. Fits of the absorbance/time data for the reaction of 5×10^{-1} M Br_2 and 1 in 1,2-dichloroethane at 25 °C to eq 5 (▣), eq 7 (◆), and eq 8 (■).

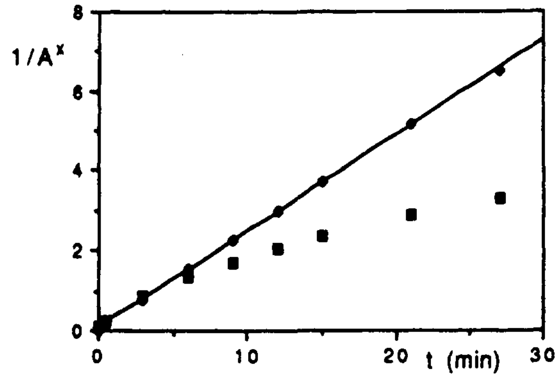

Figure 5. Fits of the absorbance/time data for the reaction of 5×10^{-1} M Br_2 and 1 in 1,2-dichloroethane at 5 °C to eq 5 (▣) and eq 7 (◆).

Table I. Third-Order and Fourth-Order Rate Constants for the Bromination of 5*H*-Dibenz[*b,f*]azepine-5-carbonyl Chloride in 1,2-Dichloroethane at 5, 25, and 50 °C[a]

$[Br_2]$	[1]	*T* (°C)	λ (nm)	k_3	k_4
2×10^{-2}	3.2×10^{-1}	50	500	$2.3\ (0.2) \times 10^{-2}$	
2×10^{-1}	2×10^{-1}	50	480	$2.0\ (0.2) \times 10^{-2}$	
3.2×10^{-1}	3.2×10^{-1}	50	540	$2.0\ (0.2) \times 10^{-2}$	
5×10^{-1}	5×10^{-1}	50	540	$2.3\ (0.2) \times 10^{-2}$	
2.2×10^{-2}	2.2×10^{-1}	25	510	$1.5\ (0.1) \times 10^{-2}$	
5×10^{-2}	5.2×10^{-1}	25	520	$1.3\ (0.1) \times 10^{-2}$	
5×10^{-1}	5×10^{-1}	25	520	*b*	*b*
2.4×10^{-2}	3×10^{-1}	5	500	$7.8\ (1.0) \times 10^{-3}$	
4.6×10^{-2}	5×10^{-1}	5	520	$1.0\ (0.1) \times 10^{-2}$	
5×10^{-1}	5×10^{-1}	5	500		$5.2\ (0.5) \times 10^{-1}$

[a] All correlation coefficients were always ≥0.999. [b] No clean third-order or fourth-order kinetics were found.

Only a *ca.* 2.5-fold increase in k_3 occurred in this 45 °C temperature interval. An Arrhenius plot gave a value of 3.45 (0.1) kcal mol^{-1} for the apparent activation energy, $E_{a(obsd)}$, of the k_3 process. In contrast, at 5×10^{-1} M Br_2 the reactions exhibited third-order kinetics at 50 °C but fourth-order kinetics at 5 °C, an intermediate situation being found at 25 °C. Thus, the shift from a third-order to a fourth-order rate law is favored by an increase in the Br_2 concentration and a decrease in temperature.

In order to check the formation of ionic intermediates at detectable concentrations, the bromination of 1 was also carried out in a conductimetric cell. As mentioned above, the reaction mixtures used for the investigation of the CTC formation did not exhibit any appreciable conductivity. Significant values were instead measured at reagent concentrations giving reasonably fast bromination rates. Typically, at 2×10^{-1} M olefin and Br_2 at 25 °C a fast initial increase in conductivity up to a value of *ca.* 4 μS cm^{-1} was observed, followed by a slow decay. A similar course, but with a higher value of the maximum conductivity (*ca.* 7 μS cm^{-1}), was found at 5 °C, while a lowest value of the maximum conductivity of 2 μS cm^{-1} was attained at 50 °C. Figure 6 shows the time course of the conductivity during the reaction of 2×10^{-1} M 1 and Br_2 at the three temperatures. In all cases the conductivity completely vanished on addition of an excess of cyclohexene, which immediately consumed all Br_2. This assured that this conductivity was not due to a stable byproduct but was rather attributable to a temperature-dependent accumulation of reversibly formed ionic bromonium–polybromide intermediates. Assuming for these species a value of the molar conductance similar to that found[11] for the adamantylideneadamantane bromonium–tribromide salt, $\Lambda^m = 25$ S cm^2 mol^{-1} at 25 °C, the maximum conductivity measured for the reaction of 2×10^{-1} M Br_2 and 1 at 25 °C should correspond to a 1.6×10^{-4} M concentration of the ionic intermediates, *i.e.*, *ca.* 0.1% of that of the starting reagents. A similar trend in conductivity, with a maximum value of 2 μS cm^{-1}, had been found at 25 °C during the much faster bromination of 5*H*-dibenz[*b,f*]azepine-5-carboxamide in 1,2-dichloroethane at 5×10^{-3} M reagent concentration.[18] In the latter case this conductivity pointed to a maximum concentration of the ionic intermediates amounting to *ca.* 2% of that of the starting reagents.

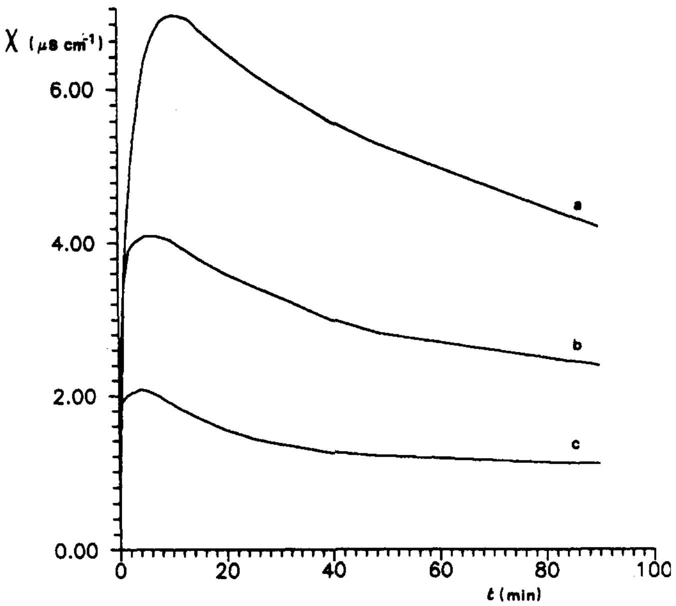

Figure 6. Conductivity/time curves of 1,2-dichloroethane solutions of 2×10^{-1} M Br_2 and 1 at 5 (a), 25 (b), and 50 °C (c).

The Bromination Product. The HPLC analysis of all the above-discussed bromination mixtures showed the formation of dibromide 2 as the only product. The structure of this dibromide had been investigated by the X-ray diffraction[5] that had shown markedly different C(10)–C(11)–C(11a) and C(9a)–C(10)–C(11) angles (121° and 113°, respectively), and a C(11)–Br(2) considerably

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[18] Bellucci, G.; Chiappe, C.; Marioni, F.; Marchetti, F. *J. Chem. Soc., Perkin Trans. 2* **1992**, 637.

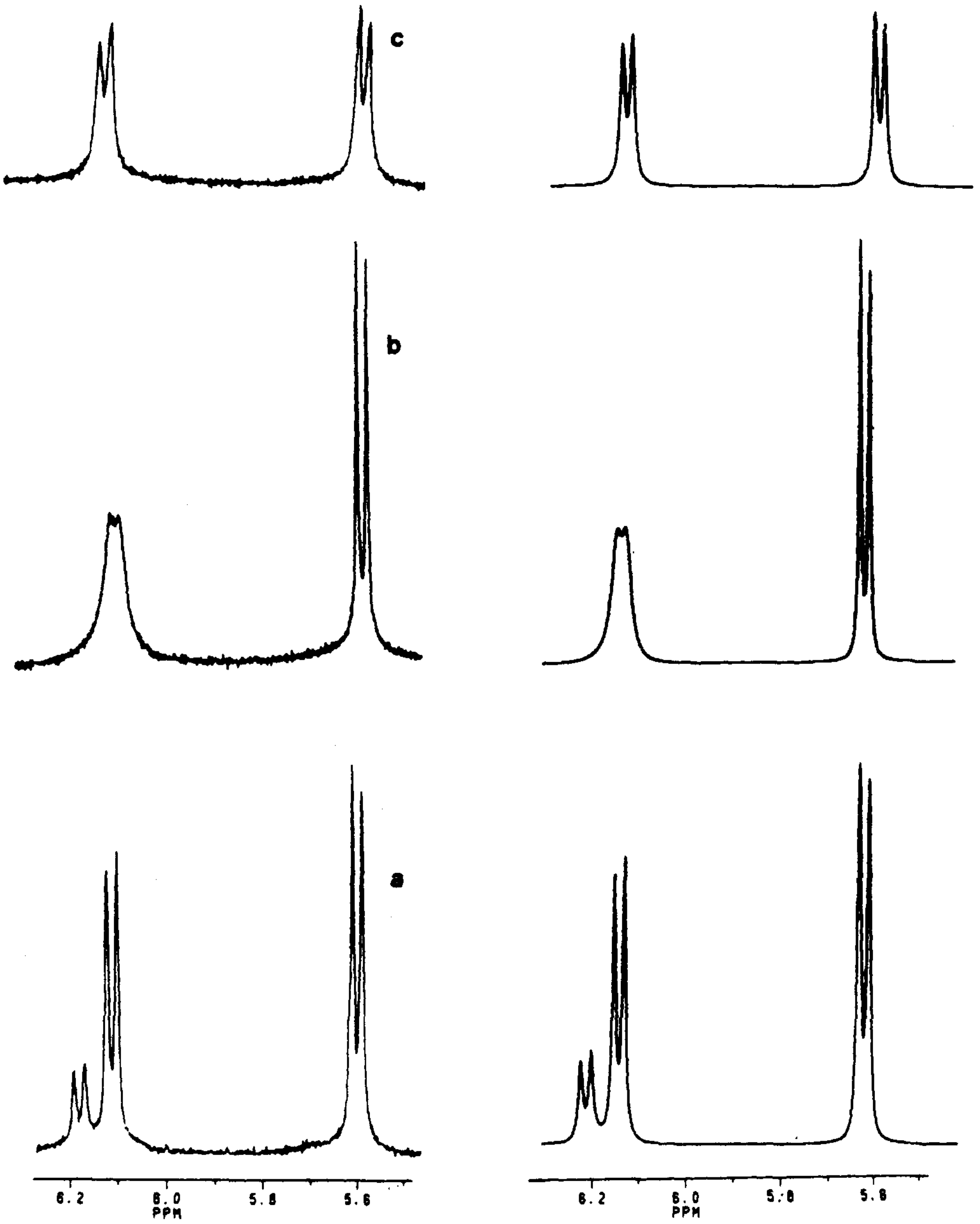
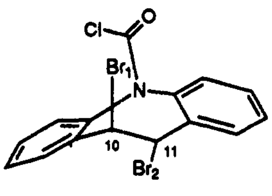
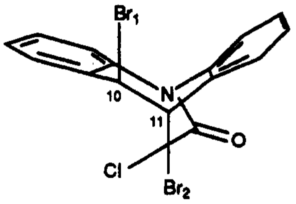


Figure 7. Experimental (left) and computed (right) band shapes of the signals of protons at C(10) and C(11) in the 200-MHz NMR spectrum of dibromide 2 in 1,2-dichloroethane-d_4 at −7 (a), 25 (b), and 55 °C (c).

longer than the C(10)–Br(1) bond (2.04 and 1.91 Å, respectively) indicating a significantly different hybridization at the carbons bearing bromine. This difference has now been confirmed by the different ^{13}C NMR chemical shifts, δ 57.99 and 62.45 ppm, of these two carbons in 1,2-dichloroethane-d_4 at 17 °C. The 60-MHz NMR spectrum of this dibromide had been reported[5] to exhibit for the protons α to Br in several different solvents an AB pattern with $J = 4.4$–4.5 Hz. The resulting antiperiplanar orientation of the two Br atoms was attributed to repulsive C–Br dipole–dipole interactions. In the present study the spectrum of **2** has been obtained at 200 MHz in 1,2-dichloroethane-d_4. Under these conditions, at 25 °C the higher field (δ 6.12) signal appeared as a very broad doublet, while the lower field one (δ 5.60) was a narrow doublet (Figure 7b). Furthermore, at higher temperature the broad 6.12 signal became a narrow doublet symmetrical to the lower field one (Figure 7c), while at lower temperature it was split in two narrow doublets with similar coupling constants, $J = 4.25$ and 4.40 Hz, in a 72:28 ratio (Figure 7a). Each of the C(10) and C(11) signals in the ^{13}C NMR spectrum was likewise split at −10 °C in two lines at δ 57.32 and 57.75, and 61.86 and 62.19, with relative intensities of about 3:1. These changes indicated a dynamic process, in which two forms of dibromide, **2a** and **2b**, both having anti-oriented bromine atoms and being nonequivalent because of the above-mentioned different angles and bond lengths at C(10) and C(11), are interconverted through a seven-membered ring inversion by torsion about the C(4a)–N(5)–C(5a) bonds, twisting of the C(10)–C(11) bond being prevented by dipole–dipole repulsions in the *gauche* conformer of the dibromide. The two *anti* conformers **2a** and **2b** have unequivalent protons α to one of the bromine atom, accidentally equivalent or slightly unequivalent protons α to the other bromine, and unequivalent carbons bearing bromine, and the medium-field part of the proton spectrum results from the overlap of two AB systems having practically identical higher field components. The markedly different population of the two conformers, corresponding to a free energy difference of 0.66 kcal mol^{-1} at 25 °C, is probably determined by the fact that in one conformer the longer C(11)–Br(2) bond is situated on the same side of the N(5) chlorocarbonyl group and experiences a repulsive interaction different from that of the form having the shorter C(10)–Br(1) bond syn to this group.



2a



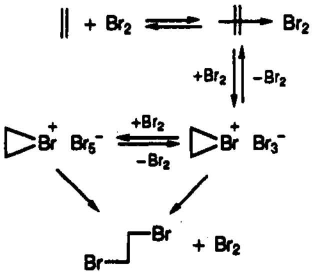
2b

In order to confirm the above interpretation of the spectrum, the dynamic process was analyzed using the band shapes of the α protons signals. A single rate process was assumed and theoretical band shapes were computed with the DNMR 3 program.[19] A set of 11 $k(T)$ values, ranging between 0.7 and 380 s^{-1}, was calculated between −10 and 55 °C. Examples of experimental and calculated band shapes are shown in Figure 7. A free activation energy $\Delta G^{*} = 16.6 \pm 0.2$ kcal mol^{-1} was then obtained using the Eyring equation. This value is identical to that found in the DNM study of *trans*-10-bromo-10,11-dihydro-11-hydroxy-5*H*-dibenz[*b,f*]azepine-5-carbonyl chloride[20] and points to the same restricted process, namely ring inversion by torsion about the C(4a)–N(5)–C(5a) bond, probably associated with restricted rotation around the N–CO bond,[21] as responsible for the existence of the two observed anti conformers of dibromide **2a** and **2b**.

Discussion

In the light of the most recent investigations, the mechanism of bromination of olefins in low polarity aprotic solvents can be represented as shown in Scheme I.

Scheme I



The involvement of 1:1 olefin–Br_2 CTCs as essential intermediates has been unequivocally demonstrated.[16] Complexes of 1:2 stoichiometry (not shown in Scheme I), although not directly observed, have also been implicated along the reaction coordinate between the 1:1 CTC and the bromonium tribromide ion pairs, on the basis of a comparison of the kinetic and thermodynamic data of reaction steps.[16] The entire set of equilibria preceeding the last product-forming step of Scheme I have been recently analyzed by UV-vis[11] and ^{1}H NMR spectroscopy[22] using adamantylideneadamantane, an unique olefin whose structure absolutely impedes the progress of the Br_2 addition beyond the stage of bromonium ion formation. These investigations have, in particular, brought to light the existence of an equilibrium between tribromide and pentabromide (and possibly higher polybromide species) in the anionic moiety of the ion pairs, at sufficiently high Br_2 concentrations. The effect of this equilibrium on the kinetics of bromination of olefins has never been investigated, mainly because the reactions of common olefins are usually too fast to be carried out at the high Br_2 concentrations required to drive the equilibrium toward the Br_5^- or higher polybromide forms.

This task has now been achieved using 5*H*-dibenz[*b,f*]-azepine-5-carbonyl chloride (**1**), an olefin so scarcely reactive toward Br_2 that its bromination can be easily followed by conventional UV–vis spectroscopy at Br_2 concentrations as high as 0.5 M. The slightly exothermal formation of a 1:1 CTC between this olefin and Br_2 has been clearly detected spectrophotometrically. A clean third-order bromination process has been found at all examined Br_2 concentrations at 50 °C, but only below 5×10^{-2} M Br_2 at 25 and 5 °C. On the other hand, a clean fourth-order (third order in Br_2) process has been found at 5 °C working at 5×10^{-1} M Br_2.

The third-order process can be evaluated, on the basis of the k_3 values reported at the three temperatures in Table I, to have a very small apparent activation energy, $E_{a(obsd)}$ 3.45 (0.1) kcal mol^{-1}. It has been shown[16] that, for a process of type shown in Scheme I, involving CTCs as essential intermediates, the apparent activation energy is related to the formation enthalpy of the CTC, ΔH, by eq 9, where

$$E_{a(obsd)} = E_a + \Delta H[1/(1 + K_f[\mathrm{Ol}])] \qquad (9)$$

E_a is the true activation energy and K_f is the CTC formation constant. Introducing the experimental values of $E_{a(obsd)}$ and ΔH and considering $K_f \leq 0.1$ M^{-1} and $[\mathrm{Ol}] \leq 0.5$ M, gives $E_a = 4.35$ kcal/mol. This activation energy is clearly too small for a reaction as slow as that of olefin **1**. Its low value cannot result from the implication along the reaction coordinate of a further step consisting in the exothermal formation of a second charge-transfer complex because the ΔH of the latter would not be much higher than that determined for the former 1:1 CTC. In order to have a true activation energy sufficiently high to account for the observed slow reaction rates one must instead assume the formation of a species having a large and negative ΔH along the reaction coordinate following the CTC formation and preceeding the rate-determining step. This species should be the bromonium–tribromide ion pair, and the rate-determining step should therefore be its collapse to dibromide **2**.

In agreement with this is the fact that ionic intermediates are accumulated during the course of the bromination of **1**, as shown by the conductivity measured in the bromination mixtures. A similar behavior was found for 5*H*-dibenz[*b,f*]azepine-5-carboxamide.[18] No conductivity was instead measurable in 1,2-dichloroethane solutions of Br_2 and *cis*-stilbene, an acyclic analogue of **1** lacking the nitrogen bridge between the *ortho* positions of the two

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phenyl rings. This indicates that the accumulation of ionic intermediates is not a common feature of olefin bromination, but is typical for the bromination of 5*H*-dibenz[*b,f*]azepine derivatives, being due to a high barrier for product formation.

A particularly high propensity of the bromonium–bromide ion pair of 1, generated by reacting *trans*-10-bromo-10,11-dihydro-11-hydroxy-5*H*-dibenz[*b,f*]azepine-5-carbonyl chloride with gaseus HBr, to revert back to olefin and Br_2 had been previously observed.[5] This high reversibility requires rate determination during the collapse of the bromonium–bromide (or polybromide) intermediate to dibromide **2**, a feature that was rationalized by a risen barrier for this step due the angle strain introduced at one of the brominated carbons of **2**, as revealed by X-ray diffraction.[5] That this strain is intrinsic to the molecular structure of **2** and is not due to crystal packing effects is confirmed by the presently reported DNMR study of dibromide **2** in the same solvent used for the bromination reaction, showing the existence in solution of two fairly rigid anti forms of dibromide **2** with largely unequivalent 10 and 11 carbons and their attached protons. Thus, both product and kinetic-thermodynamic results agree in pointing to coincident rate- and product-determining steps in the bromination of 1.

As pointed out above, a shift from an overall third-order to an overall fourth-order (third-order in Br_2) bromination process is produced by a decrease in temperature and an increase in Br_2 concentration. In principle, this suggests some form of association to higher aggregates in either molecular Br_2 or in one of the reaction intermediates preceeding the rate-determining step. Third-order terms with respect to Br_2 had been occasionally reported for olefin bromination.[23,24] Their origin was obscure, although the hypothesis of the participation of associated Br_2 molecules was proposed.[24]

No evidence has been found in this work for the presence of dimeric or trimeric forms of the halogen at 5×10^{-1} M Br_2 and 5 °C, where the reaction was overall fourth-order. In fact, no change in the molar absorptivities occurred between 5×10^{-2} and 5×10^{-1} M Br_2 all over the measurable wavelength range.

A step of the bromination mechanism of Scheme I that is certainly shifted toward the formation of higher bromine aggregates by an increase in halogen concentration and a decrease in temperature is the tribromide–pentabromide equilibrium in the anionic moiety of the ion pair intermediates. That this equilibrium is exothermic has been shown for the tetrabutylammonium tribromide–pentabromide[10] and for the adamantylideneadamantane bromonium–tribromide–pentabromide species in 1,2-dichloroethane.[22] A ΔH of *ca.* −21 to −26 kcal mol^{-1} has been evaluated for the formation of the pentabromide form from olefin and Br_2 in the latter system.[22] Unfortunately, the $E_{a(obsd)}$ for the fourth-order process could not be evaluated in the present study because the pertinent k_4 was accessible only at 5 °C. However, there is little doubt, by analogy with the above-discussed overall third-order bromination process, that also in this case the last product forming step is the rate-determining one. So, the third-order dependence of the rate on Br_2 should not result from the simultaneous involvement of three Br_2 molecules in the ionization step, but would rather be the consequence of a stepwise association of three halogen molecules into an ionic aggregate like the bromonium–pentabromide species, which undergoes rate-determining collapse to the final product. A shift in the tribromide–pentabromide equilibrium in favor of the latter at low temperature may also be responsible for the largest accumulation of ionic intermediates observed at 5 °C by conductimetric measurements, the rate of return being reduced because the bromonium–pentabromide species has to pass through the bromonium–tribromide and the CTC to revert back to the reagents.[22]

Work is in progress to check if this change from overall third-order to overall fourth-order kinetics at high Br_2 concentrations and low temperatures is a general feature of olefin bromination or is typical of olefins for which reversible bromonium ion formation can be independently established. In the latter case this could be a mechanistic criterium for rate determination during the nucleophilic step of the bromination reactions.

Experimental Section

Materials and Methods. 5*H*-Dibenz[*b,f*]azepine-5-carbonyl chloride (1) was prepared from 5*H*-dibenz[*b,f*]azepine (iminostilbene, Ega, >97%) as previously reported.[25] *trans*-10,11-Dibromo-10,11-dihydro-5*H*-dibenz[*b,f*]azepine-5-carbonyl chloride (2) was obtained by bromination of 1 as reported.[5] All products were >99.5% pure by HPLC. Commercial 1,2-dichloroethane was treated as previously described.[26] Bromine was withdrawn from 1-mL vials (C. Erba, RPE grade, >99.5%) opened immediately before use.

The ^1H NMR and ^{13}C NMR spectra were recorded in 1,2-dichloroethane-d_4 on a Bruker AC 200 instrument. UV–vis spectra and kinetic measurements were obtained with a Varian Cary 2200 instrument. Conductivities were measured with a Philips PW 9509 digital conductivity meter. HPLC analyses were carried out with a Waters Model 600E apparatus equipped with a Model 990 photodiode array detector and a Spherisorb S 5 CN column using hexane–tetrahydrofuran (99:1) as eluent at a flow rate of 1 mL min^{-1}.

Spectrophotometric and Conductimetric Measurements. Bromine solutions in 1,2-dichloroethane were prepared shortly before use and the concentrations adjusted to twice the desired initial ones. These solutions were thermostated at 5, 25, or 50 °C and mixed with equal volumes of prethermostated solutions of 1 of proper concentration in the same solvent. The spectra of solutions of 1 and Br_2 alone were also measured. For the slowest brominations, or when only the CTC formation occurred, the entire 350–550-nm range spectrum was periodically recorded. The difference absorbance–concentration data pertaining to the CTC formation were fitted to eqs 1 and 2 in order to obtain the formation enthalpy of the CTC. For the faster brominations the decay of the Br_2 absorption was monitored at 540, 520, 510, 500, or 480 nm. All reactions were followed for more than 2 half-lives. The absorbance–time data were fitted to the appropriate pseudo-second- (4), third- (5), or fourth-order rate equation (7), and the rate constants obtained are averages of three independent measurements. At the end of a few kinetic runs the product composition was checked by HPLC. Only dibromide **2**, eventually accompanied by unreacted 1, was found.

The conductivity measurements were carried out by mixing the prethermostated reagent solutions in the conductimetric cell. The conductivity was measured immediately after mixing and at 1-min intervals until the maximum value was attained and then at 5-min intervals up to 60–70% conversion.

D NMR Calculations. The spectra of 1,2-dichloroethane-d_4 solutions of **2** were taken at 11 temperatures in the −10 to +55 °C range. The chemical shifts of the sensor nuclei were assumed

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to be independent of temperature. A natural line width of 1.2 Hz was evaluated from the spectrum at −10 °C. The free energy difference between the two conformers was calculated from the population ratio measured in the spectrum at −10 °C, and the population ratios at the other temperatures were consequently determined. Band shapes were computed with the DNMR 3 program,[19] using the chemical shifts, the population ratios and the line width determined as mentioned, and with trial kinetic constants. The simulated and experimental spectra were compared visually. At temperatures higher than 30 °C a good simulation required a progressive increase of the natural line width. The Eyring equation, $k = (K_B T/h)e^{-\Delta G^\ddagger/RT}$, was employed in its logarithmic form to determine $\Delta G^\ddagger$ from experimental $k(T)$, using a least-squares fitting program. A $\Delta G^\ddagger = 16.6(0.2)$ kcal mol^{-1} was obtained. The quoted uncertainty largely overwhelms the standard deviation produced by the fitting procedure; it is evaluated by taking into account possible errors on the temperature values of up to ±3 °C and on the population ratios of up to 5%.

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