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Steric Strain and Reactivity: Electrophilic Bromination of *trans*-(1-Methyl-2-adamantylidene)-1-methyladamantane

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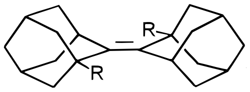
trans-(1-Methyl-2-adamantylidene)-1-methyladamantane (DMAD, **1b**) reacts with Br_2 in chlorinated hydrocarbon solvents to give either a bromonium polybromide ion pair or a substitution product, depending on bromine concentration. The first intermediate is a 1:1 π-complex having $K_f = 1.85(0.19) \times 10^3$ M^{-1} at 25 °C, which rapidly evolves to the bromonium tribromide ion pair. At high bromine concentration, which shifts all equilibria involving the counteranion of the ion pair intermediate toward the pentabromide species, this bromonium ion is stable and unable to further evolve into products. Temperature-dependent NMR spectra indicate chemical exchange of Br^+ between the sides of the plane containing the two carbons of the bromonium ion. At very low bromine concentration, no ionic intermediate is detected and the reaction rapidly yields a rearranged substitution product, identified as **10.** Under these conditions the disappearance of the π-complex follows a first-order rate law, and the observed rate constant increases with increasing olefin concentration, showing that product formation implies Br^- as counteranion of the ionic intermediate, whose formation is a reversible process. A comparison of the results reported here for the bromination of **1b** with those previously found for the parent olefin, adamantylideneadamantane (**1a**), shows that steric strain markedly affects the reactivity of the double bond.

Electrophilic bromination of olefins is one of the classical reactions in organic chemistry. Its mechanism is well documented by a large number of investigations of kinetics and products.[1] Although work in this field was mainly directed to the early steps of the reaction, and more recently[2] to the formation of bromine−olefin π-complexes[3] and to the reversibility of the ionization,[4] quantitative data, for instance about the formation constants of the first-formed π-complex, are still limited. The main difficulty in these studies arises from the high reactivity of these species. Therefore it has been a fruitful approach to extend the lifetime of these intermediates by use of sterically crowded olefins in which rapid formation of the ionic intermediate and its subsequent trapping are retarded. The first olefin used for this purpose was adamantylideneadamantane (Ad═Ad, **1a**) which showed unique behavior among all the investigated olefins. Its highly congested structure absolutely prevents the progress of Br_2 addition beyond the stage of bromonium ion formation.[5] In halogenated solvents an equilibrium between free Ad═Ad, free Br_2, the Ad═Ad-Br_2 π-complex, and bromonium tribromide, pentabromide, and heptabromide ion pairs is established instantaneously.[6] Although the spectra of these species overlap extensively, it has been possible to determine the formation constants and the electronic spectra of all these species at equilibrium.[6] Furthermore, it has been shown that this equilibrium is the source of an additional apparent plane of symmetry, equilibrating the upper and lower faces of the bromonium ion on the NMR time scale.[7]



1a R = H
1b R = CH_3

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Adamantylideneadamantane is a tetrasubstituted olefin bearing bulky "cage" substituents in which, however, no significant twisting or pyramidalization of the double bond is present.[8,9] The introduction of two *trans*-alkyl substituents at the allylic carbon atoms on the other hand markedly increases the strain of the system and is sufficient to induce a significant torsion and out-of-plane bending of the double bond. It has been calculated that the two methyl groups in the α-positions of *trans*-(1-methyl-2-adamantylidene)-1-methyladamantane (DMAD, **1b**) increase the strain energy by 21.6 kcal/mol.[9]

Although the ground-state destabilization may enhance reactivity, a detailed analysis of reactivity must consider electronic and steric factors in both ground and transition states, as has been recently suggested.[8] In principle, the introduction of bulky groups into olefins may protect the double bond and cause inertness toward addition reactions. In view of the fact that Ad═Ad represents a unique system for studying not only the ionic intermediates involved in the electrophilic addition of bromine to the double bond but also the π-complex formed in the earlier step, we decided to undertake a careful investigation of the DMAD−bromine system in 1,2-dichloroethane in order to obtain further information about the correlation between structure and reactivity.

Results

Spectrophotometric Measurements. When equal volumes of solutions of DMAD (**1b**) ($1 \times 10^{-1}-1 \times 10^{-3}$ M) and Br_2 ($2 \times 10^{-2}-1 \times 10^{-4}$ M) in 1,2-dichloroethane were mixed at 25 °C, a rapid disappearance of the bromine absorbance was observed and a colorless solution was obtained. To measure the complex properties, equal volumes of solutions of Br_2 ($1 \times 10^{-4}-2 \times 10^{-4}$ M) and of **1b** ($5 \times 10^{-4}-2 \times 10^{-2}$ M) in 1,2-dichloroethane were mixed in a stopped-flow apparatus at 25 °C, and the wavelength range between 260 and 420 nm was monitored.

The initial absorbances (A_0) measured at 290 and 300 nm immediately after mixing were significantly higher than expected on the basis of the analytically determined Br_2 concentration. They were fitted to the Scott equation[10] for a 1:1 complex, taking into account the contribution to A_0 due to the olefin ($[\mathbf{1b}]_{free} \cong [\mathbf{1b}]_{tot}$) but ignoring the small one attributable to free Br_2. Satisfactory fits were obtained, giving $K_f = 2.4 \times 10^3$ M^{-1}, $\epsilon_{300} = 1.7 \times 10^3$ M^{-1} cm^{-1}, and $K_f = 2.5 \times 10^3$ M^{-1}, $\epsilon_{290} = 3.9 \times 10^3$ M^{-1} cm^{-1}, respectively, for the 1:1 π-complex. These estimated values were used as starting parameters of the nonlinear least-squares fit (NLLSQ)[6] of the entire set of absorbances, taking into account both the free Br_2 and the olefin contribution to A_0. This yielded a final value of K_f of 1.85(0.19) × 10^3 M^{-1} at 25 °C and molar extinction coefficients of the 1:1 π-complex at all wavelengths examined (Figure 1). The root-mean-square residual of the fit was 0.032, and the correlation coefficients between the K_f and any of the ϵ never exceeded ±0.8, excluding a misleading correlation between K_f and the UV spectrum. This satisfactory fit to an equation derived for 1:1 complexes excluded any significant contribution by species of 1:2 stoichiometry like a bromonium tribromide, whose Br_3^- counteranion would absorb in the region of the charge transfer (CT) band. In the parent system, **1a**−Br_2, the impossibility to proceed beyond the formation of the bromonium polybromide species allows their accumulation at equilibrium. On the contrary, in the case of **1b,** the transformation of the ionic intermediate into the product (see below) prevents its accumulation in relevant amounts, at least under these reaction conditions. The absorption maximum, $\lambda_{max} = 270$ nm ($\epsilon_{max} = 9.74(0.36) \times 10^3$ M^{-1} cm^{-1}), is near those observed for analogous systems.[3]

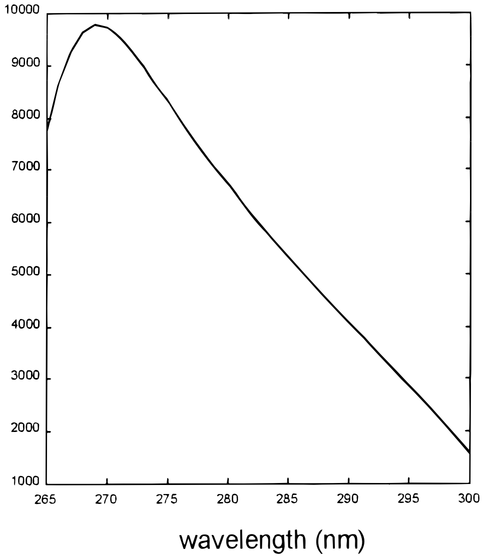

Figure 1. Computed best-fit spectrum of **2b** in 1,2-dichloroethane.

Table 1. Rates of Disappearance of 2b in 1,2-Dichloroethane at 25 °C

$[Br_2]$	[Ol]	λ	k_{obsd} (s^{-1})
5×10^{-5}	2.5×10^{-4}	280	0.035(0.005)
5×10^{-5}	5×10^{-4}	280	0.055(0.005)
1×10^{-4}	2×10^{-3}	270	0.076(0.004)
1×10^{-4}	5×10^{-3}	270	0.110(0.010)

Under the reported conditions the CT band decayed rapidly. This decay followed, for at least one half-life, the integrated first-order rate law of eq 1. Hydrogen bromide

$$\ln(A_{CT} - A_{\infty 0}) = \ln(A_{0CT} - A_{\infty 0}) - k_{obsd}\, t \qquad (1)$$

was formed during the reaction, in agreement with the product analysis. However, under anhydrous conditions, this did not interact with unreacted free bromine to give tribromide species, whose formation from HBr and Br_2 in 1,2-dichloroethane is dependent[3b] on the presence of traces of H_2O. Therefore, HBr formation affected neither the A_0 values nor the kinetic behavior. The measured rate constants, k_{obsd}, reported in Table 1, increased on increasing olefin concentration.

When diluted solutions of olefin ($[\mathbf{1b}] < 1 \times 10^{-3}$ M) were mixed with solutions of Br_2 (≥0.2 M), an equilibrium between the reactants and a new UV-absorbing species was established instantaneously, like in the case of the

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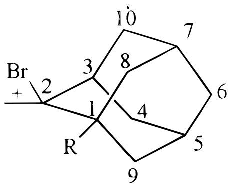
Table 2. ^{13}C Nuclear Magnetic Resonance Chemical Shift for Bromonium Ions 3b and 3a in CD_2Cl_2[a]



R = CH_3 or H

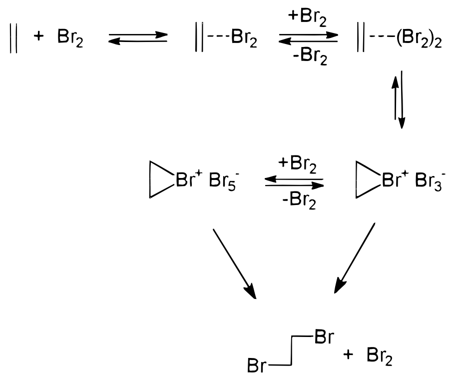
carbon no.	δ (ppm)		carbon no.	δ (ppm)	
	3b	**3a**[b]		**3b**	**3a**
2,2′	162	158.6	9,9′	49.9	42.9
1,1′	46.8	39.8	7,7′	27.9	29.3
3,3′	40.8	39.8	5,5′	27.2	29.3
8,8′	52.2	45.0	6,6′	35.7	38.8
10,10′	40.1	45.0	CH_3	32.6	
4,4′	43.0	42.9			

[a] 17 °C; ppm using CD_2Cl_2 as internal reference. 50.3 MHz using a Bruker AC 200 spectrometer. [b] Reference 12.

parent olefin.[6] Since under these conditions the equilibrium mixtures were stable, it was possible to investigate them with conventional UV−vis spectrophotometric and NMR techniques. The shapes of the absorption curves measured between 270 and 420 nm were in agreement with an equilibrium between Br_3^- and Br_5^- ions. On the basis of extinction coefficients of these two salts in 1,2-dichloroethane, adopted from both tetrabutylammonium tribromide and pentabromide[11] and adamantylideneadamantane bromonium tribromide and pentabromide[6] ion pairs, and from the formation constant of Br_5^- from Br_3^-, previously found for the Ad═Ad system,[6] a practically complete transformation of the olefin **1b** into the corresponding bromonium salts was evaluated. UV spectra indicated the presence of Br_5^- and Br_3^- anions. The ^{13}C NMR spectra of CD_2Cl_2 solutions of **1b** (ca. 10^{-2} M) and Br_2 (>2 M) consisted of an 11-line pattern (Table 2), which could be attributed on the basis of DEPT experiments and by comparison with the spectra reported[12,13] by Olah et al. and Brown et al. to the bromonium ion of **1b**, the *trans*-(1-methyl-2-adamantylidene)-1-methyladamantane bromonium pentabromide ion pair **3b**. Increase in temperature caused broadening and eventually coalescence of the signals at 52.2 and 49.9, 43.0 and 40.1, and 27.9 and 27.2 ppm. Removal of bromine by washing with an aqueous $NaHSO_3$ solution restored the spectrum of pure **1b**. This, together with the kinetic measurements and the NMR data, showed that the formation of the ionic intermediate is a reversible process.

When solutions of olefin **1b** at low concentration (2×10^{-3}−5×10^{-3} M) were mixed with solutions of Br_2 (1×10^{-2}−4×10^{-1} M), a slow disappearance of the absorbance at 340 nm, attributable to the ionic intermediates was observed. At 25 °C the reaction followed a clean first-order rate law. The observed kinetic constant k_{obsd} increased from $2.3(0.2) \times 10^{-3}$ to $4.6(0.2) \times 10^{-3}$ s^{-1} when the bromine concentration decreased from 0.2 to 0.075 M. The kinetics, observed in the presence of a large excess of bromine and in the presence of a large excess of olefin,

Scheme 1



were not affected by the addition of isoamyl nitrite. The possibility that the disappearance of Br_2 is caused by a competing free radical bromination process was thus safely excluded.

Products. The product distribution arising from the reaction of **1b** with bromine was studied by both NMR and GC-MS techniques. Reaction in dichloromethane of **1b** with a small excess of bromine at 0 °C in the dark rapidly predominantly yields a single product (>90% in the crude reaction mixture). On the basis of the mass spectrum ($C_{22}H_{29}Br$, $M = 372/374$) and NMR spectra, we propose structure **10**.

Discussion

In light of the most recent investigations,[1−4] the mechanism of Br_2 addition to olefins in aprotic chlorinated solvents can be represented as shown in Scheme 1. The involvement of 1:1 and 1:2 π-complexes as essential intermediates has been demonstrated unequivocally.[3a,3f] By using congested olefins it has been possible to obtain information about the nature of these complexes.[3e] Furthermore, the entire set of equilibria preceding the last product-forming step of Scheme 1 has been analyzed by both UV−vis and NMR spectroscopy using adamantylideneadamantane,[6,7] whose structure impedes the product-determining step. These investigations have shown that the ionic intermediates are in equilibrium with the π-complex formed first. They also have 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 which depends on temperature and Br_2 concentration.[6,7]

As pointed out previously, the carbon−carbon double bond of Ad═Ad (**1a**), although highly congested, is essentially planar.[9] The introduction of the two methyl substituents in the bridgehead position of the adamantane moiety (**1b**), in the allyl-positions to the double bond, causes twist of the double bond (10.5° as calculated by means of the force field MM2[9]). This, as shown by the results reported here, markedly influences the reactivity of the system affecting every single step of the reaction. In the case of the 1,1'-diethyl derivative of Ad═Ad, an X-ray structure is available. Twist angle (12.3°), out-of-plane bending (10.6°), and bond elongations near the double bond are reasonably reproduced by MM2 calculations.[9] This demonstrates the applicability of this force field to hydrocarbons of type **1b**.

(i) Formation of a π-Complex between 1b and Br_2. Spectroscopic data obtained immediately after mixing of the reagents show that the reaction of bromine with **1b**

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occurs through the initial formation of a 1:1 π-complex. Its stability constant ($K_f = 1.85(0.19) \times 10^3$ M^{-1} at 25 °C) is about six times higher than that found[6] for **1a**, $K_f = 298$ M^{-1}. It is the highest value reported for a complex of this type in 1,2-dichloroethane at 25 °C. Representative values are available for cyclohexene[3a] (0.47 M^{-1}), tetraisobutylethylene[3b] (9.71 M^{-1}), *d,l*-D_3-trishomocubylidene-D_3-trishomocubane[3c] (7.69×10^2 M^{-1}), (*E*)-2,2,3,4,5,5-hexamethylhex-3-ene[3d] (84 M^{-1}), (*E*)-2,2,5,5-tetramethyl-3,4-diphenylhex-3-ene[3f] (1.2 M^{-1}), and tetraneopentylethylene[3g] (1.6 M^{-1}).

Several factors are important in promoting high formation constants, and the physical nature of binding is probably more complicated than it is generally assumed. Olefin and bromine are solvated before binding with related ΔH_{solv}. On complexation, the enthalpic contribution, ΔH, arises from the direct olefin$-$Br$_2$ interaction, and this parameter is affected, as suggested,[2] by the number and nature of the substituents. These influence the electron-donating ability of the alkenes (leading to a low ionization potential), as well as the steric crowding around the double bond which can preclude an optimal interaction in the π-complex. Furthermore, in the unbound state, olefin and bromine have overall rotational and translational entropy ΔS_{RT}. In particular olefins bearing flexible substituents, able to adopt different low-energy conformations, have an internal entropy, ΔS_{int}, owing to conformational degrees of freedom. Upon binding, both ΔS_{RT} and ΔS_{int} decrease, even if they are partially compensated by the entropic contribution due to the liberation of solvent molecules and by the new low-frequency vibrational modes associated with the noncovalent olefin$-$Br$_2$ interaction.

The very restricted conformational mobility of the "cage" substituents in **1a**,**b** and *d,l*-D_3-trishomocubylidene-D_3-trishomocubane, affecting both the internal entropy (ΔS_{int}) and the ability to shield the double bond, probably significantly contributes to the much larger K_f values found for the π-complexes of these olefins, compared to other alkenes. However, the cage nature of the substituents is not sufficient to explain the relative stability of the three complexes. Therefore, as a first step toward understanding the different K_f values found, the correlation between K_f and the ionization potentials (IP) of these olefins was inspected. Since the IP is closely related to the energy of the highest occupied molecular orbital (HOMO), these energies were calculated by a semiempirical method (PM3). The values obtained for ethylene, *d,l*-D_3-trishomocubylidene-D_3-trishomocubane and the cage alkenes **1a**,**b** are −10.642 000, −9.413 063, −9.180 109, and −9.193 76 eV, respectively. The order obtained for the cage olefins does not reflect their K_f values.

Different solvations of **1a**,**b** can, at least in part, be responsible for the observed behavior. However, an alternative, more appealing explanation may be that the formation of the π-complex in the case of **1b** relieves a part of the strain energy present in the ground state. In other words, steric interactions between a methyl group and the hydrogen atom which determine the structural deformation of the double bond and increase the energy of **1b** with respect to **1a** can be less dominating in the π-complex than in the ground state of **1b**, thus increasing the energy difference in the exothermic reaction profile.

(ii) Kinetics of Disappearance of the 1b−Br$_2$ π-Complex. Whereas the parent olefin **1a** always yields a stable bromonium salt in equilibrium with the π-complex and reagents, in the case of **1b** the stability of the ionic intermediate strongly depends on reaction conditions. It is observed only in the presence of a relatively high bromine concentration, which shifts all the equilibria involving the couteranion toward the pentabromide species. When the reaction is carried out using an excess of olefin, or in the presence of a very low bromine concentration, practically no ionic intermediate is detected and the reaction rapidly yields a substitution product and HBr. The dependence of this reaction on bromine concentration suggests that the proton abstraction from an intermediate, or from a first formed product, implies the involvement of Br$^-$ as a base, while the basicity of polybromide anions does not suffice. The bromine concentration affects the ability of Br$_3^-$ to give Br$^-$ via the Br$_2$−Br$_3^-$ equilibrium ([Br$^-$] = [Br$_3^-$]/K[Br$_2$]).[11,14]

The disappearance of the CT band of **2b** follows a first-order rate law. This is in agreement with the involvement of a bromide ion in the reaction. It has been shown that the rate of disappearance of the total Br$_2$ is given by eq 2 if the alkene−Br$_2$ π-complex is a reactive intermediate

$$-\mathrm{d}[\mathrm{Br}_2]_t/\mathrm{d}t = k_2[\pi\text{-complex}][\mathrm{Br}_2] \tag{2}$$

$$-\mathrm{d}[\pi\text{-complex}]/\mathrm{d}t = k_2[\pi\text{-complex}]^2 \tag{3}$$

and reacts with free Br$_2$ in the rate-determining formation of the ionic intermediate, namely the bromonium or bromocarbenium tribromide.[3a] From this a second-order rate law for the disappearance of the π-complex can be obtained (eq 3).

On the other hand, if the rate-determining step is the transformation of the bromonium (or bromocarbenium) bromide (**3-Br$^-$**) into the product, k_p in Scheme 2, eq 4

$$-\mathrm{d}[\mathrm{Br}_2]_t/\mathrm{d}t = k_p[\mathrm{OlBr}^+\mathrm{Br}^-] \tag{4}$$

can be written. On the basis of the equilibrium between OlBr$^+$Br$^-$ and OlBr$^+$Br$_3^-$ (eq 5), as well as between OlBr$^+$Br$_3^-$ and the π-complex (eq 6), eq 7 can be obtained, where K_D is K_3/K_3'.

$$[\mathrm{OlBr}^+\mathrm{Br}^-] = [\mathrm{OlBr}^+\mathrm{Br}_3^-]/K_3'[\mathrm{Br}_2]_f \tag{5}$$

$$[\mathrm{OlBr}^+\mathrm{Br}_3^-] = K_3[\mathrm{Br}_2]_f[\pi\text{-complex}] \tag{6}$$

$$[\mathrm{OlBr}^+\mathrm{Br}^-] = (K_3/K_3')[\pi\text{-complex}] = K_D[\pi\text{-complex}] \tag{7}$$

Under steady-state conditions the total bromine concentration should be expressed by eq 8. The total halogen is given by eq 10, taking into account the equilibrium between π-complex and reagents (eq 9).

$$[\mathrm{Br}_2]_t = [\mathrm{Br}_2]_f + [\pi\text{-complex}] \tag{8}$$

$$[\pi\text{-complex}] = K_f[\mathrm{Br}_2]_f[\mathrm{Ol}] \tag{9}$$

$$[\mathrm{Br}_2]_t = [(1 + K_f[\mathrm{Ol}])/K_f[\mathrm{Ol}]][\pi\text{-complex}] \tag{10}$$

Introduction of eq 7 and 10 into eq 4 yields eq 11, in which the observed first-order rate constant for the disappearance of the π-complex (k_{obsd}) can be expressed by eq 12.

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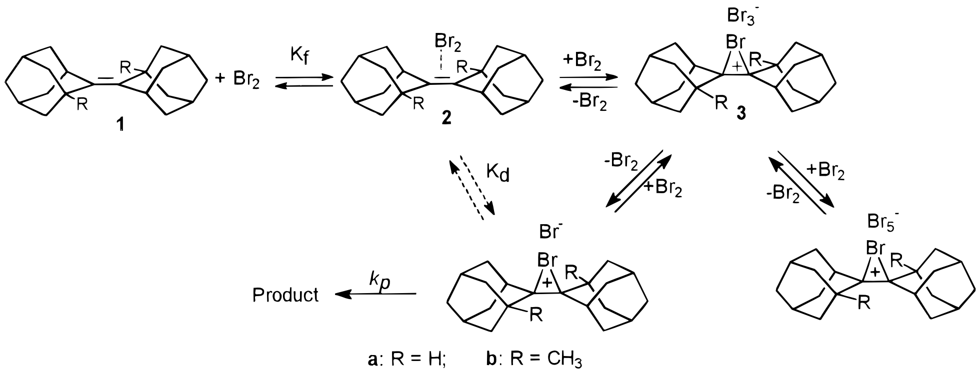
Scheme 2



$$-d[\pi\text{-complex}]/dt = [k_pK_fK_D[\mathrm{Ol}]/(1 + K_f[\mathrm{Ol}])][\pi\text{-complex}] \quad (11)$$

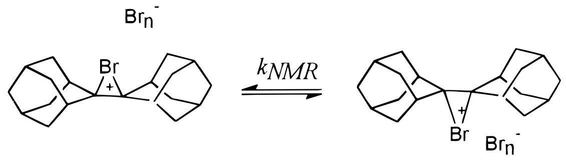
$$k_{obsd} = k_pK_fK_D[\mathrm{Ol}]/(1 + K_f[\mathrm{Ol}]) \quad (12)$$

Rearrangement of eq 12 gives eq 13. When the reactions are carried out in the presence of an excess of olefin, a plot of $1/k_{obsd}$ vs 1/[Ol] should give a straight line and the ratio of the slope to the intercept give the formation constant of the π-complex.

$$1/k_{obsd} = 1/k_pK_fK_D[\mathrm{Ol}] + 1/K_Dk_p \quad (13)$$

It is noteworthy that not only the disappearance of the π-complex in the reaction of **1b** with Br_2 follows eq 11 and, at least under the present reaction conditions, the observed first-order rate constant increases with increasing olefin concentration (in agreement with eq 12) but the K_f calculated by applying eq 13, $2.06(0.2) \times 10^3$ M^{-1}, is in good accordance with the value found independently by the fitting procedure on the basis of the initial absorbances. These data therefore confirm that the product formation implies the Br^- species as counteranion of the ionic intermediate. Analogy with the parent olefin and the analysis presented are consistent with the process in Scheme 2, where there is an equilibrium formation of $Ol-Br^+/Br^-$, followed by a rate-determining proton abstraction from the latter. However, kinetics alone cannot be used to prove unambiguously this point.

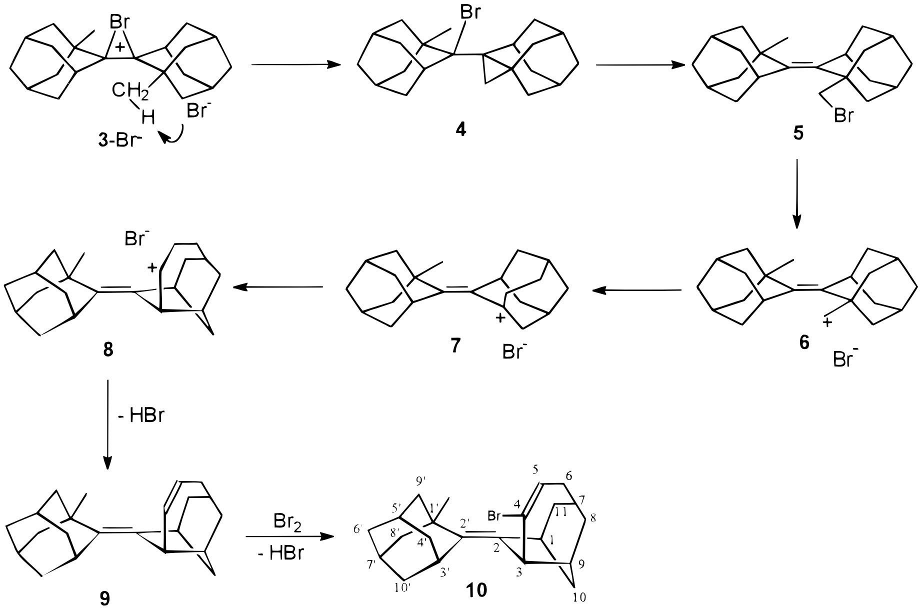
(iii) Detection of the Ionic Intermediate. In the presence of a large excess of bromine **1b** gives an ionic intermediate (**3b**) sufficiently stable to allow NMR investigations, in analogy to the parent olefin **1a**. Before we discuss the ^{13}C NMR spectrum of **3b**, it must be stressed that **1b** possesses a 2-fold proper axis of symmetry (C_2) and only one σ plane perpendicular to it containing the two carbon atoms of the double bond, different from the parent olefin which contains an additional σ plane containing the aforementioned C_2 axis.[7] The corresponding bromonium ion is characterized exclusively by the proper axis of symmetry (C_2). The perpendicular σ plane is lost. It may be an "effective" symmetry element only under conditions in which there is a fast chemical exchange of Br^+ between the two faces of the molecule. For the parent olefin, **1a**, a dynamic NMR investigation has shown[7] that the equilibrium between bromonium tribromide, π-complex, and reagents is the source of the apparent equivalence of the two sides of the molecule of the ionic intermediate in ^1H NMR spectrum. However, high bromine concentrations and/or low temperatures shifts the equilibrium into the direction of bromonium ions and thus slows down the movement of the Br^+ from one side to the opposite. Under these conditions the NMR signals of the two sides of the molecule are separated. Furthermore, the apparent plane of symmetry is lost also when the equilibrium between ionic intermediates and reagents is removed by replacing the polybromide counteranions with a nonnucleophilic triflate.[13] Addition of a trace of **1a** again provides a symmetrization mechanism, and this apparent plane of symmetry is recovered.[13]



The ^{13}C NMR spectrum of **3b** presents only C_2 symmetry, at least under conditions where the ionic intermediate is sufficiently stable to allow NMR measurements. However, on the basis of the previously obtained results with **1a**,[7] it is possible to hypothesize that the presence of a large excess of bromine on the NMR time scale slows down the exchange of the Br^+ between the two sides of the plane containing the two carbons of the bromonium ion. In agreement with this supposition a broadening of some signals on increasing temperature, which indicates a dynamic process, has been observed also for **3b**. The signals of C-8/9, C-4/10, and C-5/7 broaden and eventually coalesce. Although a line-shape analysis of these signals has not been carried out, owing to the very limited interval of temperature and/or bromine concentrations in which observation of the dynamic process is possible, this behavior confirms that the formation of the ionic intermediate is a reversible process even for this olefin and the rate of return of the ionic intermediate to the reagents depends on the nature of the counteranion, as for the parent olefin. On the other hand, the recovery of **1b** when dichloromethane solutions of **3b** and Br_2 were washed with an aqueous $NaHSO_3$ solution is further evidence of a reversible formation of the ionic intermediate.

Although an 11-line pattern of the type found for **3b** (Table 2) is consistent either with a bridged ion or with a rapidly equilibrating pair of partially bridged ions, as well as with two rapidly equilibrating 2-bromocarbenium ions, the chemical shift of the quaternary carbons C_2 and $C_{2'}$ (at δ 162 ppm) excludes a completely open carbenium ion, for which a value of $\delta = 200$ ppm would be expected.[12] On the basis of the NMR data, and taking into account

Scheme 3



the reactivity of the system, the ionic intermediate therefore most likely is a rapidly equilibrating pair of partially bridged species. The high steric strain present in **1b** may be at least partially relieved if the ionic intermediate, which for the sake of simplicity is represented in Schemes 2 and 3 as a bromonium ion, has some bromocarbenium ion character. Furthermore, a partially bridged intermediate, always able to return to reagents, may explain the higher propensity of **1b** to give substitution products with respect to the parent olefin, **1a**. It has been shown indeed recently[15] by X-ray analysis that the chloronium ion of Ad═Ad, which in contrast with the bromonium ion easily gives homoallylic substitution products, is characterized by C−Cl bonds of different length. This feature has been rationalized[15] on the basis of a structure in which chlorine is σ bonded to a single carbon center, and the cationic charge of the adjacent center is stabilized by the chlorine lone pair acting as an n-donor. Also for this salt the ^{13}C NMR spectrum consisting of seven lines is in agreement with an apparent plane of symmetry which bisects the halonium ring, indicating that the ionic intermediate is present in solution as two rapidly equilibrating ion pairs.

(iv) Reaction Products. Reaction of **1b** with bromine at 0 °C in dichloromethane and in the dark rapidly yields a predominant product. On the basis of its mass spectrum ($C_{22}H_{29}Br$) and NMR spectra, we propose structure **10**. This is based on the absence of one of the methyl groups originating from **1b**, on the connectivities C5−C6−C7−C11−C1 and C3−C9 established by ^{1}H-TOCSY- (short mixing time) and ^{1}H-homo-decoupling experiments, on the ^3J(C,H) cross-peaks C5−3-H, C3−5-H, and C4−6-H and ^2J(C,H) C4−3-H (HMBC experiment), and further on consistent 135° DEPT and HMQC experiments.

A conceivable pathway to the formation of **10** combines known reactions of adamantane derivatives:

(1) Electrophilic bromination at the homoallylic methyl group to yield **5**. Analogous reactions of Ad═Ad (**1a**), the parent olefin, have been described. Whereas reaction with bromine yields a stable bromonium ion, several reagents which combine an electrophilic and a sufficiently basic moiety (benzenesulfenyl chloride,[16] benzeneselenyl chloride,[17] and NCS[18]) stereospecifically lead to homoallylic substitution products. This has been attributed to proton abstraction from the homoallylic methylene group which is acidified by the adjacent onium ion (analogue of **3-Br**$^-$ in Scheme 3) and subsequently by sterically driven ring opening of the intermediate cyclopropyl methyl derivative (analogue of **4** in Scheme 3).[19]

Analogously, the ionic intermediate **3b-Br**$^-$ could experience homoallylic proton abstraction by bromide ion and rearrangement to give a substituted bromomethyl cyclopropane derivative (**4**), which in turn rearranges to give **5**. At low bromine concentration the relatively basic Br$^-$ predominates whereas at higher concentration the equilibrium is shifted toward less basic polybromide anions,[11,14] thus preventing this reaction. In the parent alkene (**1a**) substitution occurs at C-4; however, in alkene **1b** the homoallylic methyl group appears to be more easily accessible. In addition, orbital overlap between homoallyl cation and bromonium ion is expected to be much easier in this case.

(2) Two successive Wagner−Meerwein rearrangements of the corresponding carbocation allow enlargement of the ring and deprotonation to yield the tricyclic alkene **9**. The conversion of **6** to **7** represents a homoallylic rearrangement via a delocalized homoallylic cation structure.[22] Analogous rearrangements of derivatives of type **5** via **6** to **7** have been observed under superacid conditions.[20] An analogous rearrangement of the parent carbon

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skeleton, in the opposite direction, has been reported (4-homoprotoadamantane to 1-methyladamantane).[21] In the present case the possibility of formation of the double bond and relief of its strain might reverse the equilibrium. Bromination/dehydrobromination finally would yield product **10**.

Conclusions

A comparison of the results reported here for the bromination of **1b** with the previous ones for **1a** shows a marked affect of steric strain on the reactivity of the double bond. It modifies the stability of the reagent and of all intermediates involved on the reaction coordinate.

(1) DMAD reacts with bromine instantaneously to form a π-complex which further evolves rapidly to the ionic intermediate. The formation constant of the π-complex (1.85×10^3 M^{-1} at 25 °C) is about six times higher than that reported for **1a** (2.89×10^2 M^{-1} at 25 °C). We interpret the strong increase of the equilibrium constant, K_f, as a result of the steric effect of the two methyl groups: the enthalpy of the alkene is increased to a greater extend than that of the π-complex.

(2) Kinetic measurement of the disappearance of the CT band of **2b** during the reaction of **1b** with Br_2, at very low halogen concentrations, indicates that the transformation of the ionic intermediate into the reaction product implies Br^- as counteranion. The observed rate law requires proton abstraction to be the rate-determining step. Therefore, since all steps preceding the rate-limiting one(s) must have lower activation energies, the ionic intermediate should be formed reversibly.

(3) UV and NMR investigations on **1b** at high bromine concentrations show that the ionic intermediate is unable to evolve to product when the counteranion is a less basic polybromide species.

(4) The ionic intermediates arising from bromine addition to **1a**,**b** are characterized by different reactivities, which may be attributed to the different steric strain in the two systems. The higher propensity of **1b** to give a homoallylic substitution products with respect to the unsubstituted compound, **1a**, could be caused by a less pronounced bridging of the ionic intermediate, and this could be a consequence of attempts to at least partially relieve the steric strain present in the ground state.

Experimental Section

trans-(1-Methyl-2-adamantylidene)-1-methyladamantane (**1b**) was prepared as previously reported.[9] Flash chromatography (silica gel G60, hexane) and recrystallization from methanol yielded plates of mp 88 °C. Raw products contained 10−20% of an isomeric compound (GC-MS) with practically identical mass spectrum, most probably the cis isomer. However, attempts to purify this compounds were not successful so far.

1,2-Dichloroethane (DCE, Fluka, puriss. pa ACS) was used as supplied without further purification. Bromine was withdrawn from 1-mL vials (C. Erba, RPE grade > 99.5%) opened immediately before use.

Spectrophotometric Measurements. 1,2-Dichloroethane solution of **1** and Br_2 were prepared by weighing the reagents in accurately calibrated volumetric flasks. The Br_2 solutions were stored in the dark and checked spectrophotometrically for their concentrations. They were discarded when the absorptions around the Br_2 UV minimum (280−350 nm) were found to be higher than expected.

For the measurements of K_f of the 1:1 π-complex, equal volumes of solutions of **1** and of Br_2, prethermostated at 25 °C, were mixed in a stopped flow apparatus equipped with a diode array detector[3d] (mixing time $\leq$ 1 ms) coupled to a data acquisition system. Absorbances were recorded at several wavelengths in the 260−420 interval (260, 270, 272, 275, 280, 290, 300, 310, 390, 400, 410, and 420 nm). At least three independent determinations were carried out for each couple of reagents.

For the determination of K_f the initial absorbances (A_0) at 290 and 300 nm were fitted to the Scott equation in order to obtain a preliminary evaluation. The composite A_0 data for all runs were fitted by the nonlinear least-squares procedure previously described[6] and yielded both K_f and the extinction coefficient at the measured wavelengths.

The first-order kinetic constants (k_{obsd}) were obtained by fitting the $A(t)$ values recorded at each wavelengths to eq 1. Reproducible values of k_{obsd} were obtained at each wavelength; average values are the k_{obsd} summarized in Table 1.

Solutions for the spectrophotometric measurements were adjusted by mixing solvent and aliquots of reagent stock solutions. The UV spectra were measured immediately at 25 °C in 0.1 or 1 cm cells, as required, in a Cary 220 instrument in the range 250−500 nm. Stability of the solutions was always checked by consecutive measurements. Under conditions in which the solutions were not stable, the kinetics were measured by monitoring the decrease of absorbance at 340 nm.

Product Study. *2-(1-Methyl-2-adamantylidene)-4-bromotricyclo[5,3,1,0^{3,9}]undec-4-ene (**10**).* Precooled dichloromethane solutions (6.3 mL each) of 18.8 mg (63 μmol) of **1b** and 70−140 μmol of bromine were mixed at 0 °C and stirred in the dark. After 10 min the solution appeared colorless; after 20 min volatile components were removed by means of a rotary evaporator, and the residue was recrystallized twice from methanol (−20 °C). GC-MS: *m*/*e* (374 (26), 372 (26) ($C_{22}H_{29}Br$; M^+), 293 (100) $(M - Br)^+$. ^1H NMR ($CDCl_3$): $\delta = 5.92$ (dd, $J_{5,6a} = 1.1$, $J_{5,6b} = 2.9$ Hz, 1H; H-5), 3.58 (d, $J_{3,9} = 8$ Hz; 1H; H-3), 3.33 (m, 1H; H-1), 3.82 (quint, $J \approx 3$ Hz, 1H; 3′-H), 2.67 (m, $J_{gem} = 16.3$ Hz, $J_{5,6a} = 1.3$ Hz, $J_{6a,7} = 8.3$ Hz, 1H; H-6a), 2.33 (m, 1H; H-9), 2.16 (m, 1H; H-7), 2.10 (dtr., $J_{gem} = 16.3$ Hz, $J_{5,6b} = 2.5$ Hz, $J_{6b,7} = 2.5$ Hz, 1H; H-6b), 1.92 (m, 2H; H-5′, H-7′), 1.81 (m, 1H; H-11a), 1.76−1.34 (m, 13H), 1.25 (m, 2H; CH_2), 1.18 ppm (s, 3H, CH_3). ^{13}C NMR ($CDCl_3$): $\delta = 145.44$ (4), 139.69, 134.10 (2, 2′), 98.32 (5), 50.98 (3), 48.85, 47.22 (8′, 9′)*, 40.57 (10′)*, 39.72 (11), 39.10 (1′), 38.41 (1), 37.47, 37.07 (6′,6)*, 36.30 (10)*, 34.93 (9), 33.50 (3′), 33.12 (4′)*, 31.14 (CH_3), 29.68 (8)*, 29.47 (7), 28.63, 28.39 ppm (5′, 7′) (assignments by 135° DEPT, HMQC, TOCSY, HMBC, and homodecoupling experiments; asterisk indicates overlapping ^1H signals, assignments proposed solely by shift arguments.)

^{13}C NMR Measurements of the Ionic Intermediate. All NMR solutions were prepared immediately before use and kept in the dark during manipulation. [**1b**] was ca. 10^{-2} M, and the [Br_2], in large excess (2 M). ^{13}C NMR spectra were recorded using a Bruker AC 200 or a Bruker AM 360 instrument. When solutions of **3b** in CD_2Cl_2 were washed with an aqueous $NaHSO_3$ solution, the spectrum of **1b** was recovered.

PM 3 calculations were performed by the standard methods with HyperChem version 7.0, Autodesc Inc., 1996; see also: Stewart, J. J. P. *MOPAC 7.0*; F. J. SeilerLab., USAF Academy, Boulder, CO; 1993.

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