

Reactivity of Homoallylic Substituted Adamantylideneadamantanes with Bromine. Substituent Effects on the Stability of the Ionic and Nonionic Intermediates

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Sterically congested adamantylideneadamantanes (**1b–g**) (X = Br, Cl, F, OH, OEt, OCOCH₃), homoallylically substituted with equatorial groups (X), react with bromine in 1,2-dichloroethane to give a stable bromonium ion intermediate or a substitution product depending on the nature of the substituent and on the bromine concentration. The nature of the substituent markedly affects the formation constant of the 1:1 π -complexes, as well as of the formation constant and reactivity of bromonium ion intermediates. The different reactivity of the ionic intermediates, which depends on the nature of substituents, is attributed to bromonium or bromocarbenium character of the intermediate, with the support of theoretical investigations. Ab initio calculations on 1:1 adamantylideneadamantane–Br₂ complexes (**2a–f**) show that the substituent affects the stability of these species through electrostatic and dispersion effects. Solvent effects may also contribute to modulate the relative stability of these species.

Halogenation of organic compounds is an important step in the preparation of various synthetic intermediates or products. Therefore, it is not surprising that electrophilic halogen addition reactions, and in particular bromination of olefins, have been widely examined, as it is well documented¹ by a large variety of kinetic and product investigations. Furthermore, as the consequence of the synthetic utility, a large number of halogenation reagents, some of these polymer-bound, have been proposed in the last 20 years.² It is probably more surprising that, despite the large number of papers published, there is still some fundamental work to be performed in this field. Many recent mechanistic studies deal with the reactivity of sterically encumbered olefins,³ and they are mainly focused on the early steps of electrophilic bromination of the double bond, such as the stability and nature of the initially formed π complexes, often named charge-transfer complexes (CTC), and the reversibility of their ionization to the ionic intermediate. Crowded

double bonds indeed enable a return to the reagents because of a slow product-forming step caused by steric retardation of the nucleophilic trapping of the congested bromonium ions. In this context, important mechanistic information has been obtained by studying the reaction of adamantylideneadamantane (AdAd, **1a**) with Br₂ in chlorinated solvents.⁴ The nature of the highly congested structure of the double bond absolutely prevents the progress of Br₂ addition beyond the stage of bromonium ion formation, and an equilibrium among free AdAd, free Br₂, AdAd–Br₂ π complex, bromonium tribromide, and pentabromide ion pairs is established instantaneously. UV measurements have given information about the relative stability of all these species in solution while

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TABLE 1. Formation Constants and Molar Extinction Coefficients at 270 nm and 25 °C for the Br₂: 1a–f Complexes Obtained from the NLLSQ Fitting of Spectral Data

	1a ^a	1b	1c	1d	1e	1f	1g
K ₁₁ (M ⁻¹)	289	492 (17)	44 (2)	123 (16)	2274 (400)	134 (10)	173 (9)
K ₁₂ (M ⁻²)	3.23 × 10 ⁵	4.6 (0.1) × 10 ⁵	295 (26)	884 (61)	–	–	3.8 (0.3) × 10 ³
K ₁₃ (M ⁻³)	7.2 × 10 ⁶	1.7 (0.2) × 10 ⁷	5.07 (0.3) × 10 ³	9.7 (0.3) × 10 ³	–	–	1.7 (0.2) × 10 ⁵
ε ₂₇₀ (M ⁻¹ cm ⁻¹)	17780 (100)	14063 (110)	6200 (83)	1435 (50)	8100 (125)	14750 (120)	2770 (95)

^a From ref 4.

corresponding ionic intermediates. In this case, to measure the properties of the eventually formed π complexes, equal volumes of Br₂ (1 × 10⁻⁴–2 × 10⁻² M) and of **1e** or **1f** (2 × 10⁻⁴–2 × 10⁻¹ M) were mixed in a stopped-flow apparatus, equipped with a diode array detector, at 25 °C, and the initial absorbances were collected in the wavelength range between 270 and 340 nm.

Finally, the stability of mixtures obtained from **1d** and **1g** depended on reagents concentration; solutions containing equimolar amounts of Br₂ and **1d** or **1g** (ranging from 1 × 10⁻³ to 2 × 10⁻² M) or an excess of Br₂ ([**1**] = 1 × 10⁻³, 1.5 × 10⁻³ < [Br₂] < 2 × 10⁻²) or, in the case of **1d**, a moderate excess of olefin ([Br₂] = 1 × 10⁻³, 2 × 10⁻³ < [**1d**] < 1 × 10⁻²) were sufficiently stable to be investigated using a conventional UV–vis spectrophotometer and the spectral data were collected in the 250–500 nm wavelength range. Solutions containing an excess of **1g** ([Br₂] = 1.6 × 10⁻⁴, 1 × 10⁻³ < [**1g**] < 4 × 10⁻²) showed a very fast disappearance of the coloration. The absorbances vs time were therefore registered in the stopped-flow apparatus between 270 and 340 nm.

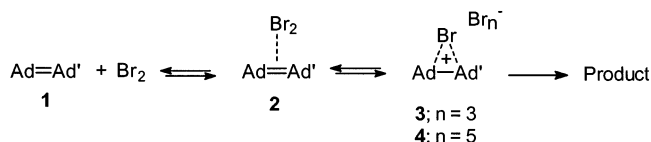
All the spectrophotometric measurements related to olefins **1b–g** were fitted using the NLLSQ computational procedure previously used for **1a**.⁴ Fitting parameters were the formation constants K_{m,n} of the A_mB_n complexes, defined from olefin and bromine (A stand for olefin, B for Br₂, the (m,n) pair having the value 1:1, 1:2, and 1:3), and the extinction coefficients of the 1:1 π complexes, the spectra of salts **3** and **4** being fixed at the values respectively reported for Bu₄N⁺Br₃⁻ and Bu₄N⁺Br₅⁻.⁸

$$[A_m B_n] = K_{mn} [A]^m [B]^n \quad (1)$$

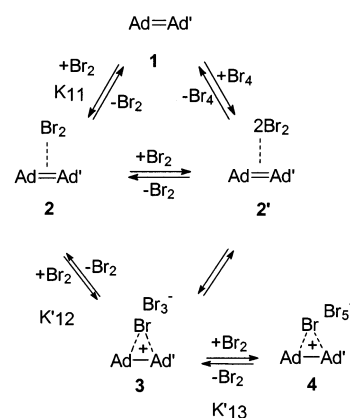
Satisfactory fits to an equation derived exclusively for 1:1 complexes were found in the case of **1e** and **1f** (rms deviations 0.042 and 0.051 absorbance units, respectively). This result excluded for both olefins any significant contribution to the initial absorbance by species of 1:2 stoichiometry like a bromonium tribromide, whose Br₃⁻ counteranion would absorb in the region of the π complex charge-transfer band. In the case of **1e** and **1f**, therefore, the transformation of the ionic intermediate into the product (see below) probably prevents its accumulation in the reaction medium, at least under the experimental conditions, and the generally accepted mechanistic pathway for bromination (reported in Scheme 1) may be proposed.

At variance, the presence of more species (**2**, **3**, and **4**) in equilibrium must be considered to obtain good fits (rms deviations < 0.05 absorbance units) of the data in the cases **1b**, **1c**, **1d**, and **1g** (Scheme 2). In analogy with **1a**,

SCHEME 1. Mechanistic Pathway for Electrophilic Bromination of 1e and 1f



SCHEME 2. Species at Equilibrium Formed by Addition of Br₂ to DCE Solution of 1a–d and 1g



the formation of **3** was too fast to be followed even with a stopped-flow apparatus.

Therefore, it was impossible to check experimentally if **3** was formed directly from **1** and Br₂, or through the complex **2** or **2'**. No evidence have been found in the present work about the formation of this latter complex. This species was observed at higher bromine concentrations in the case of tetraeneopentylethylene, an olefin whose reaction with Br₂ stops at the stage of π complexes.^{3c} For these reasons the formation constant of **3** was defined in the computational procedure, as in the case of **1a**, from **1** and Br₂, with m=1 and n=2. The formation constant related to the bromine-assisted ionization of **2** is K₁₂' = K₁₂/K₁₁. Although the formation constant of bromonium pentabromide salt **4** was again defined in the computational procedure from **1** and Br₂, with m=1 and n=3, there is, however, no doubt that **4** arises from **3** and Br₂. The pertinent formation constant is K₁₃' = K₁₃/K₁₁. In Table 1 are reported the formation constants K₁₁, K₁₂, and K₁₃ and the extinction coefficients of the π complexes species for the parent system, **1a**–Br₂, are also reported.

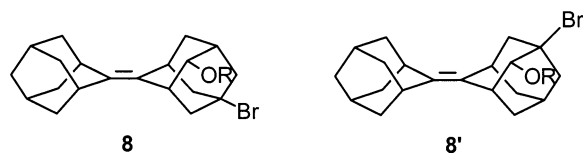
The values of the formation constants of the 1:1 π complexes (K₁₁) computed in the present work for olefins having strictly related structures show that the stability of these intermediates is considerably affected by the presence of a polar substituent. An ethoxy or acetoxy group, as well as a fluorine atom, only slightly reduces the value of the formation constant with respect to the

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parent olefin, but a more important effect has been observed when X is a chlorine atom. In contrast a bromine atom increases the formation constant even if the most marked effect has been observed when X is an hydroxy group. The formation constant of **2e** ($K_{11} = 2274 \text{ M}^{-1}$) at 25 °C is about 1 order of magnitude higher than that evaluated for the analogous complex of **1a**, and this is the highest value reported for a complex of this type in DCE.

In these derivatives the position of the substituent at C4 (equatorial) excludes the possibility that the stability of the π complexes, also in the case of the syn adducts, may be affected by shielding effects of the double bond and suggests that the main effect should be of electronic nature, at least in the case of single atom substituents (Br and Cl) and hydroxy group. Inductive and/or field effects may be invoked, although resonance effects, due to σ -conjugation of the substituent lone pair with the C2 p orbital through the aligned C3–C4 bond cannot be excluded. However, attempts to correlate the K_{11} values of **2a–g** with some substituent parameters, such as σ_F , σ_α , σ_X , and σ_R , which should account respectively for field, polarizability, electronegativity, and resonance effects,⁹ failed, suggesting that more than one electronic effect probably contributes to the stability of these complexes. Considering the limited number of data in our hands, we have not applied a multiparameter equation to correlate the K_{11} values. Ab initio calculations have been instead performed on the π complexes **2a–f** (see below).

2. Reaction Products. In analogy with the parent olefin **1a** compounds **1b–d** and **1g** react with an excess of Br_2 to give ionic intermediates sufficiently stable to allow NMR investigation. Detailed studies are now under way to further investigate the features of these ionic species. At variance the reaction of **1f** with an equimolar amount of bromine at 0 °C, in DCE or dichloromethane- d_2 , and in the dark rapidly yields a nonionic reaction product and HBr. The mass spectrum of the product (90% yield) suggests the formation of a substitution compound containing a bromine atom ($\text{C}_{22}\text{H}_{31}\text{BrO}$). The ^{13}C NMR spectrum (200 MHz) is characterized by the presence of the double bond and of a quaternary carbon at 69.6 ppm attributable to bridgehead carbon bearing a bromine atom. Furthermore, this carbon should be present on the same adamantyl ring bearing the OEt group; the CH_2 protons of ethoxy group become diastereotopic due to the presence of a new chiral center. Finally, considering the chemical shift values of the starting olefin and of the product, and the difficulty to insert a bromine atom on the allylic carbon we propose structure **8** or **8'** for this compound.



A similar structure may be attributed, on the basis of the NMR spectra of the crude reaction mixture, to the

main product formed from **1e**. In this case, however, the spectra evidenced the presence of other products (30–40%).

The different stability of the ionic intermediates arising from olefins **1a–g** that are able to give substitution products or remain in solution in equilibrium with the reagents, depending on substituent nature, may be attributed to a different charge distribution on the bromonium ion intermediate. A more pronounced β -bromocarbenium character of the cationic moiety of the intermediate is probably necessary so that the intermediate undergoes to product. Theoretical calculations (see below) show a higher difference of charge on the two carbons of the bromonium ring of **3e** when compared with **3c**. Furthermore, the observed dependence of the stability of the ionic intermediate **3** on bromine concentration, in the case of **1g**, show that also the nature of the counteranion may affect the ability of the intermediate to evolve to products. At high bromine concentrations the counteranion is mainly present in solution as Br_5^- or Br_7^- (not reported in Scheme 1) and to the lower basicity of these anions, with respect to Br_3^- or Br^- , may be attributed the increased stability of the ionic intermediate. A very similar behavior has been recently observed in the reaction of *trans*-(1-methyl-2-adamantylidene)-1-methyladamantane with Br_2 in DCE.³¹

3. Theoretical Investigation of π Complexes and Bromonium Ions. To obtain information on the effect of substituent on the stability of the intermediates of the electrophilic bromination of olefins, we have performed ab initio calculations on the previous described systems, and in particular we have considered the olefin– Br_2 π complexes for **1a–f** (X = H, Br, Cl, F, OH, OEt) and the bromonium ions for **1a** and **1e** (X = H, OH).

To find a level of calculation that gave an appropriate description of these systems with a reasonable computational cost, especially for π complexes, was not easy. The widely used density functional methods failed on such type of complexes.¹⁰ Some low-end many-body methods, like MP2, worked fine but were too expensive. Furthermore, a basis set rich of polarization and diffuse function was required to give good results. Thus, the following strategy has been chosen: all the geometries of olefins, π complexes, and bromonium ions were refined at a B3LYP level. On the final geometry a two-layer hybrid ONIOM¹¹ calculation was performed using MP2 on the model system and B3LYP on the real system. The model system was constituted by the bromine atoms, the quaternary (sp^2) carbons, the X atoms, and the four hydrogen at the homoallylic carbons near the π complex.

The CEP-121G¹² basis set, augmented by polarization and diffuse function on the atoms of the model system, was used. The calculations in DCE solution were performed using the IEF-PCM continuum model. The electrostatic, cavitation, dispersion, and repulsion interactions were considered. All the calculations have been performed using the Gaussian 99 Package.¹³ The results are summarized in Tables 2–12. The use of a many body method, at least for the reaction site, was required.

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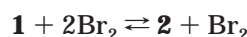
TABLE 2. Relative Energies (ΔE , kcal mol⁻¹) of Species **2** and **3** Calculated in Vacuo at B3LYP Level with Respect to **1** and Br₂

X	2Br ₂ + 1	Br ₂ + 2	3
H	0.00	-2.95	67.73
F	0.00	-2.05	—
Cl	0.00	-1.87	72.29
Br	0.00	-1.70	—
OH	0.00	-16.53	69.04
OEt	0.00	-2.44	—

TABLE 3. Relative Energies (ΔE , kcal mol⁻¹) of Species **2** and **3** Calculated in Vacuo at ONIOM Level with Respect to **1** and Br₂

X	2Br ₂ + 1	Br ₂ + 2	3
H	0.00	-9.66	64.75
F	0.00	-8.23	—
Cl	0.00	-11.91	75.13
Br	0.00	-13.21	—
OH	0.00	-31.10	59.84
OEt	0.00	-17.46	—

The values reported in the Tables 2 and 3 refer to the equilibria:



The large differences between the data reported in these tables show a marked effect of the substituents (F, Cl, Br, OH, and OEt) on the stability of intermediate **2** and **3**.

In this theoretical study we have considered only π complexes and bromonium ions in which the attack of the bromine molecule occurred on the same side of the substituent (syn adducts). The main purpose of these calculations was that to find a qualitative explanation for the substituents effect on the stability of the intermediates **2** and **3**. In particular, for the very high stability of the π complex arising from **1e** (X = OH). It is evident that the anti adducts should have a stability nearer to that of the complex arising from **1a** being the role of the substituent, locate at the opposite site, smaller than in the syn complexes. The differences in stability of the π complexes between bromine and olefins **1a–g** should be therefore mainly due to the syn adducts.

In agreement with the experimental data, the calculated “behavior” of hydroxy derivative **1e** is different from that of the other olefins; the relative energy of its π complex (bonding energy) is larger than the other ones at both levels of calculation. Furthermore, very different values characterize the bonding energies of all the other complexes confirming the influence of the substituent on

TABLE 4. Bonding Energies (kcal mol⁻¹) in the π Complexes: Comparisons between ONIOM and B3LYP Results.

X	B3LYP	ONIOM	Δ
H	-2.95	-9.66	-6.71
F	-2.05	-8.23	-6.18
Cl	-1.87	-11.91	-10.04
Br	-1.70	-13.21	-11.51
OH	-16.53	-31.10	-14.57
OEt	-2.44	-17.46	-14.92

TABLE 5. Population Analysis for the π Complexes **2a–f**

X	Br(1)	Br(2)	C(1)	C(2)	X	R ^a
Mulliken Population Analysis in Vacuo						
H	0.075	-0.303	-0.645	-0.645	0.19	
F	0.012	-0.186	-0.657	-0.560	-0.321	
Cl	0.010	-0.174	-0.700	-0.580	-0.223	
Br	0.011	-0.175	-0.641	-0.689	-0.124	
OH	0.015	-0.209	-0.424	-0.811	-0.665	0.433
OEt	0.026	-0.204	-0.642	-0.710	-0.428	0.182
NBO Population Analysis in Vacuo						
H	0.041	0.271	0.017	0.017	0.173	
F	-0.027	0.161	-0.007	0.017	-0.444	
Cl	-0.029	-0.159	-0.006	0.016	-0.144	
Br	-0.029	-0.151	-0.003	0.015	-0.062	
OH	-0.027	-0.179	0.030	0.015	-0.769	0.445
OEt	-0.026	-0.181	0.007	0.014	-0.623	0.311

^a R = H or Et.

these species. To facilitate the comparison in Table 4 are reported the bonding energies of π complexes **2a–f** calculated at the B3LYP and ONIOM level, together with their difference.

To explain the different stability of the π complexes in term of substituents effect, we have analyzed the trends which characterize the bonding energies of the π -complexes **2a–f**, taking into account the population analysis, reported in Table 5, and the electron density maps of complexes **2a–f**, given as Supporting Information.

On the basis of the data reported in Table 4, we can observe that when X is an halogen, at the DFT level, to the fluorine atom, according to both NBO and Mulliken population analysis, correspond the most stable complex but, at the ONIOM level, there is an opposite trend and the olefin bearing the bromine atom gives the most stable complex. A simple interpretation of these results can be given considering that at the B3LYP level the electrostatic (or inductive) effects are predominant, but at the ONIOM level the dispersion forces (London forces), that increase in magnitude with number and mobility of electrons, are better considered.

The strong effect of the OH substituent can be also evidenced looking at the population analysis (Table 5) and at the density maps. Also in this case we have performed both NBO and Mulliken population analysis. The NBO analysis does not correlate to the bonding in the π complex: it recognizes the olefin and the bromine as separate fragments. The resulting population analysis reflects this fact: the charges on the complexation site are not sensitive to the nature of the substituent. Instead the Mulliken population analysis is very sensitive: indeed, there are significant differences in the charges of the two carbons involved in the complexation in the case of the hydroxyl derivative **1e** (X = OH). Looking at the

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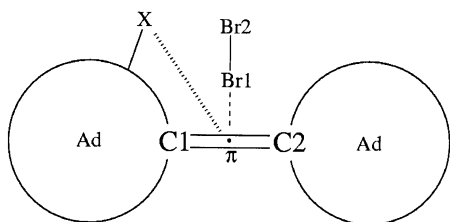


FIGURE 1. Distances and angles reported in Table 6. The distances in the figure are not in scale.

TABLE 6. Geometrical Parameters of π Complexes **2a–f** (distances in angstroms, angles in degrees)

X	π -Br1	Br1- π -C2	π -X
H	2.41	90.0	2.48
F	2.75	89.9	3.79
Cl	2.77	89.9	4.10
Br	2.77	89.9	4.62
OH	2.71	88.1	3.74(O)
			3.90(H)
OEt	2.71	89.7	4.29(O)
			4.86(C $_{\alpha}$)
			6.00(C $_{\beta}$)

density maps, the difference is evident: the maps for X = H, F, Cl, Br, OEt are almost identical but the map for the OH-substituted olefin is evidently asymmetric, showing a strong effect of the substituent on the complexation site.

The large difference in bonding energy calculated for the two π complexes arising from **1e** and **1f** (X = OH and X = OEt), which is qualitatively in agreement with the computed K_{11} values, reported in Table 1, can be instead explained considering the steric hinderance due to the ethyl group that, at variance with hydrogen, is able to interpose itself between the O atom and the complexation site.

Then, to give a possible interpretation of the higher stability of the π complex of olefin **1e**, we have given attention to some molecular properties. At first we have taken into account some geometrical quantities: two interatomic distances and a bond angle. These geometrical quantities are depicted in Figure 1 and reported in Table 6.

We define as π the middle point of the C–C double bond and take under consideration the distances π -Br1 and π -X as well as the angle Br1- π -C2. The values of Br1- π -C2 angle show no significant deviation from the regular T-shape of the **2a** (X = H) complex. Only the value for the **2f** complex (X = OH) is slightly larger. A substantial difference instead characterizes the Br1- π distance in the complex of the unsubstituted olefin (**2a**) with respect to all the other ones (**2b–f**): it is shorter by about 0.3 Å. The last geometrical quantity taken under consideration is the distance between π and X. The halogen series shows an increasing distance on going from F to Br, due to the increasing length of the carbon-halogen bond. The OH group is instead the closest to the π complex site.

Table 7 reports the comparison between the formation constants of the complexes, K_{11} , arising from the spectrophotometric measurements, and their theoretical estimations on the basis the olefin polarizability (eq 2). We have recently found¹⁴ that for alkyl-substituted olefins

TABLE 7. Calculated Polarizabilities of the Olefins **1a–f** (α) and Experimental (K_{11}) and Theoretical (K_f) Formation Constants of the Related π Complexes, **2a–f**. Polarizabilities, in Atomic Units, Were Computed at the B3LYP

X	experimental		theoretical		
	K_{11}	$\log(K_{11})$	α	estimated $\log(K_f)$	$\log(K_f) - \log(K_{11})$
H	289	2.46	214.03	2.75	0.29
F	123	2.09	213.14	2.74	0.65
Cl	44	1.64	226.39	2.98	1.32
Br	492	2.69	233.95	3.13	0.44
OH	2274	3.36	217.05	2.81	-0.55
OEt	134	2.13	243.90	3.32	1.19

TABLE 8. NBO Deletion Analysis of π Complexes **2a–f**

	ΔE	pop. π^* (before)	pop. π^* (after)	δ
H	0.05	0.14103	0.14101	-0.00002
F	2.19	0.14696	0.14756	0.00060
Cl	7.32	0.09745	0.08635	-0.01110
Br	7.26	0.09757	0.08637	-0.01120
OH	15.55	0.10362	0.08853	-0.01509
OEt	4.41	0.10331	0.10311	-0.00020

there is a linear relation between the polarizability π of the olefin and the constant of formation of the π -complex olefin-Br₂:

$$\log(K_f) = -1.2985 + 0.018942\pi \quad (2)$$

The set of olefins used in parametrization does not contain heteroatoms and encloses **1a**. The difference between the estimated formation constants, $\log(K_f)$, and the experimental values, $\log(K_{11})$, shows that the linear relation is strictly valid only in the case of a pure dispersion interaction.

Table 8 contain the results of a NBO deletion analysis. It is possible in the NBO package to delete selected interactions among groups of orbitals to estimate the contribution of these interactions to the molecular electronic energy.

We have deleted the interaction between the occupied orbital located on the substituent atoms and the virtual orbital on the atoms involved in the π complex (C1,C2,-Br1,Br2) and vice versa. This is equivalent to delete the charge-transfer interaction according to the Morokuma scheme of decomposition of the energy.¹⁵ The difference in the molecular electronic energy is very large in the case of X = OH. The orbital that shows the larger difference in population before and after the deletion is the C1-C2 π^* .

These latter data lead therefore to the following statements:

(1) The presence of a substituent in the homoallylic position leads to a weakening of the dispersion interaction between bromine and the C1-C2 π bond but introduces new interactions among the substituent and the C1,C2,Br1,Br2 atoms. This is supported by the fact that the π -Br1 distance is larger in **2b–f** complexes than in **2a**. The sum of these two contributions leads to the total stabilization energy of the complex.

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TABLE 9. Comparison between Ethylene- and **1a**-Br₂ π Complexes. Values in kcal mol⁻¹, except Entropies in cal mol⁻¹ K⁻¹. The ONIOM and MP2 Free Energies Are Evaluated Using the B3LYP Entropies

	Ad=Ad		H ₂ C=CH ₂	
	DFT	ONIOM	DFT	MP2
ΔE_{cplx}	-2.95	-9.66	-3.42	-4.27
$\Delta E_{\text{def Br}_2}$	2.12	4.35	0.33	1.39
$\Delta E_{\text{def C=C}}$	3.87	3.48	0.06	0.04
ΔE_{bond}	-8.95	-11.61	-3.81	-5.70
ΔS_{tot}	29.34	-	27.32	-
ΔZPE	34.02	-	0.84	-
$\Delta E_{\text{thermal}}$	-32.51	-	3.08	-
ΔE_{tot}	-1.44	-8.15	0.5	-0.35
ΔG_{tot} (298 K)	-10.18	-17.52	-7.68	-8.49

(2) These new interactions are related to the nature of the substituent and to its distance from the complexation site.

To investigate the nature of this new interaction we must look to the data in Tables 6, 7, and 8:

(1) The three halogens, which can be considered almost spherical, show an increasing polarizability and an increasing distance from the interaction site.

(2) The OH group is the closest and shows a permanent dipole.

(3) The OEt group is similar to OH, but its distance from the interaction site is larger and its dipole is smaller than the one of the OH group.

(4) The data of Table 8, which give an estimation of the charge transfer interaction (in the orbital language corresponding to the dispersion interaction), show that this interaction is considerably strong in the case of X = OH.

We can therefore conclude that the OH and OEt group interact with the π -complex through a dipole-dipole interaction while the halogens interact with induced dipole-dipole interactions.

This interaction is very strong in the case of X = OH that shows a large dipole and is near to the interaction site.

For the other substituents there are discrepancies between the experimental and theoretical values but for these systems the differences are smaller and more sensitive to the accuracy of both theoretical and experimental techniques.

To obtain further information about these complexes we have then compared the π complex of the parent olefin, **2a**, with the analogous complex of ethylene. The related data are reported in Table 9. The thermal and entropic corrections has been calculated according to Ben-Naim scheme.¹⁶

Although no data is reported in the literature about the formation constant of the ethylene-Br₂ π complex, the K_f value for a simple disubstituted alkene (cyclohexene-Br₂) is 0.47 M⁻¹,¹⁷ in agreement with calculations for ethylene, and very far from the value found for **1a**.

To explain the higher stability of the complex arising from **1a** with respect to ethylene we should consider that the stabilization energy of the complex may be decomposed in three terms: the positive contribution of defor-

TABLE 10. Relative Energies (ΔE , kcal mol⁻¹) Calculated in DCE at B3LYP Level

X	2 Br ₂ + 1	Br ₂ + 2	3
H	0.00	-4.69	-1.66
F	0.00	-1.25	-
Cl	0.00	-1.12	2.75
Br	0.00	-0.99	-
OH	0.00	-15.88	-10.73
OEt	0.00	-1.60	-

TABLE 11. Extrapolated Relative Energies in DCE at ONIOM Level

X	2 Br ₂ + 1	Br ₂ + 2	3
H	0.00	-11.40	1.32
F	0.00	-7.43	-
Cl	0.00	-11.16	5.59
Br	0.00	-12.50	-
OH	0.00	-30.45	-1.53
OEt	0.00	-16.62	-

mation of the two reagents, the difference of energy of the reagents frozen at the complex geometry with respect to the equilibrium geometry, and the bond term evaluated as the difference. In the case of **1a** we have large deformation terms that take into account the steric hindering in the related complex. The resulting bonding energy is about double for **2a** with respect to ethylene. We can therefore formulate two hypotheses for this difference: (1) In the complex of **1a**, the halogen is hosted in a "molecular pocket" in which there are stabilizing interactions between the Br₂ molecule and the adamantyl groups. (2) The pyramidalization of the double bond in **2a** promotes the complexation of the halogen molecule. Probably, both effects contribute to the higher stability of **2a**. It is noteworthy that the entropic contributions to the formation of the π complex for these two olefins are nearly equal. The main contribution to ΔS is given by the relative motions of the Br₂ with respect to the olefin. There are five normal modes with frequencies less than 100 cm⁻¹ in which the Br₂ and olefin move nearly as rigid bodies.

Another interesting point is the role of the solvent on the stability of these intermediates. Table 10 reports the relative energies evaluated for the π complexes and bromonium ions at B3LYP level in DCE, while in Table 11 an extrapolation for values in solution at the ONIOM level is presented. The values reported in this latter table are $E(\text{Table 11}) = E(\text{Table 10}) + E(\text{Table 3}) - E(\text{Table 2})$.

On the basis of the data reported in Tables 10 and 11, we can state that the solvent contribution destabilizes all the complexes, with the exception of the parent olefin **1a**. This occurs because the substituted olefins are more stable in solution than the adamantylideneadamantane. In the complex the substituent atoms are only partially exposed to the solvent. Thus in the complexes the differences are less emphasized. It must be remarked that solvent contribution is able to qualitatively reproduce the relative stability of the π complexes arising from **1b** (X = Br) and **1c** (X = Cl) with respect to the corresponding complex of the parent olefin.

Finally, it is noteworthy that the Mulliken charge analysis on the ionic intermediates arising from **1a**, **1c**, and **1e** (X = H, Cl, OH), reported in Table 12, shows that

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TABLE 12. Mulliken Charges (in a.u.) Obtained in Vacuo and in DCE at B3LYP Level for the Bromonium Ions **3a,c,d** (Rd = H)

X	Br	C(1)	C(2)	X	R
H/vacuo	0.216	-0.554	-0.554	0.193	-
H/DCE	0.217	-0.559	-0.559	0.219	-
Cl/vacuo	0.208	-0.367	-0.760	-0.134	-
Cl/DCE	0.226	-0.441	-0.708	-0.173	-
OH/vacuo	0.210	-0.407	-0.677	-0.628	0.430
OH/DCE	0.207	-0.335	-0.775	-0.657	0.451

the bromonium ion **3d** is characterized by a significant difference of charge on the two carbons of the bromonium ring. More negative charge is present on the carbon C(2) far away from the substituent, and this is in agreement with the hypothesized structure able to explain the peculiar reactivity.

A more detailed analysis of the theoretical features will be presented in a separate paper.¹⁸

Conclusions

The results reported for bromination of several derivatives of adamantylideneadamantane (**1b–g**) show that the presence of a polar substituent at the homoallylic position markedly affect the reactivity of the system modifying the stability of all intermediates. In particular, they show that:

(1) All the derivatives react quickly with bromine to form the corresponding π complexes in equilibrium with the reagents. Furthermore, these complexes are in equilibrium also with the ionic intermediates, when X = F, Cl, Br, or OAc. In the latter case the ability of the ionic intermediate to evolve to product depends on bromine concentration. The formation constant of the π complexes **2b–f** depends on the substituent nature. Ab initio calculations show that the constant is mainly affected by dipole–dipole or induced dipole–dipole interactions due to the substituent at C-4. The calculated higher stability of complex **2a** with respect to the corresponding complex of ethylene may be attributed to the fact that in the complex of **1a** the halogen is hosted in a “molecular pocket” where stabilizing interactions between the Br₂ molecule and the adamantyl groups exist. Furthermore, the pyramidalization of the double bond in **2a** may favor the complexation of the halogen molecule. Finally, calculations show that a solvent effect, due to the different ability of the medium to solvate the substituent in the free olefin and π complex, may also contribute to modulate the relative stability of the π complexes of the substituted olefins **1b–g**.

(2) The ability or not of the ionic intermediates to undergo to products, depending on the substituent nature, may be attributed to a different bridging in the ionic intermediates. Ionic intermediates having a more β -bromocarbenium character are probably more prone to evolve to products. In agreement, ab initio calculations show a higher difference of charge on the two carbons of the bromonium ring of **3e** with respect to **3c**.

(3) Finally, a careful choice of substituent at C-4 can give chiral halonium ions to use in the asymmetric halogenation of unsaturated compounds.

Experimental Section

Adamantylideneadamantane (**1a**) was prepared according to the procedure described by Lenoir.¹⁹ The 4-equatorial chlorine, bromine, fluorine, hydroxy, ethoxy, and acetoxy derivatives of **1a** (**1b–g**) were prepared as previously reported.^{20,21}

1,2-Dichloroethane (DCE, puriss. p.a. ACS) was used as supplied without further purification. Bromine was withdrawn from 1-ml vials (RPE grade > 99.5%) opened immediately before use.

Spectrophotometric Measurements. To preliminarily verify the stability of the bromonium ion intermediates 1,2-dichloroethane solutions of olefins **1b–g** were mixed with equal volumes of equimolar Br₂ solutions in the same solvent. The UV spectra were measured immediately in the range 250–500 nm, and the stability of the solutions was checked by consecutive periodic measurements. Olefins **1b** and **1c** gave equilibrium mixtures which were stable for at least 30 min, and olefins **1e** and **1f** reacted quickly with bromine to give uncolored solutions, while the stability of the solutions arising from the mixing of **1d** or **1g** and Br₂ depended on the relative concentrations.

To determine the formation constants of all the species present at equilibrium, 1,2-dichloroethane solutions of **1b** or **1c** or **1d** or **1g** and Br₂ were prepared by weighing the reagents in accurately calibrated volumetric flasks. The Br₂ solutions were stored in the dark and checked spectrophotometrically for their concentrations. They were discarded when the absorption around the Br₂–UV minimum (280–350 nm) were found to be higher than expected.

Working-strength solutions were prepared by mixing solvent and aliquots of the reagent stock solutions withdrawn with precision microburets. The analytical concentrations of Br₂ and olefin are reported in the text. The UV spectra were registered at 25 °C in 1 or 0.1 cm cells in the 250–420 nm range. An already described nonlinear least-squares procedure was applied to fit the spectrophotometric data. The root-squares deviations of the fittings for **1b**, **1c**, **1d** and **1g** were always <0.05 absorbance units.

For the measurements of K_f values of the 1:1 π -complexes of Br₂ and **1e** or **1f**, equal volumes of solutions of these olefins and of Br₂, prethermostated at 25 °C, were mixed in a stopped flow apparatus equipped with a diode array detector. Absorbances were recorded at several wavelengths in the 270–350 interval. At least three independent determinations were carried out for each couple of reagents.

For the determination of K_f values, 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 to yield both K_f values and the extinction coefficients at all the measured wavelengths.

Product Study. To precooled DCE (or dichloromethane-*d*₂) solutions (0.5–2 mL) of **1f** (ca. 30–120 mg) an equimolar amount of Br₂ was added at 0 °C in the dark. After complete disappearance of the color (1–2 min), the samples were directly analyzed by NMR, when the reactions were carried out in the deuterated solvent, or after removal of the volatile components by means of a rotary evaporator when the reactions were carried out in DCE. The residue was purified by short column filtration on silica gel using hexane to yield **8** or **8'** (R = Et), 90% yield, as a colorless oil. GC-MS: *m/e* (390 (5), 392 (5) (C₂₂H₃₁BrO: M⁺), 311 (19) (M – Br), 49 (100). ¹H NMR (CD₂-Cl₂); δ = 3.6 (m, 2H, OCH₂CH₃); 3.35 (br, 1H); 3.2 (br, 1H);

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2.94 (br, 1H); 2.85 (br, 2H); 2.65 (m, 2H); 2.42 (dd, 2H); 2.20–1.60 (m, 19H); 1.22 (t, $J = 7$ Hz, CH₃). ¹³C NMR and DEPT (CD₂Cl₂); $\delta = 137.9$ (=C); 129.0 (=C); 86.4 (CHO); 69.6 (quaternary C, CBr); 65.4 (CH₂O); 49.6 (CH₂); 43.2 (CH₂); 40.0 (CH₂); 39.8 (3CH₂); 38.8 (CH); 37.8 (CH₂); 37.5 (CH₂); 35.4 (CH); 32.9 (CH); 32.7 (2CH); 31.6 (CH₂); 28.9 (2CH); 15.8 (CH₃). Anal. Calcd for C₂₂H₃₁BrO: C, 67.51; H, 7.98; Br, 20.42. Found: C, 67.48; H, 7.93; Br, 20.50.

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Supporting Information Available: Fully optimized Cartesian coordinates of structure **2a–f**, **3a**, and **3e**, their calculated total energies, keywords adopted for the Gaussian calculations, and a figure of the density maps for π complexes **2a–f** at the DFT level. This material is available free of charge via Internet at <http://pubs.acs.org>.

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