# Cation−$\pi$ Interactions in the Gas Phase Methylation of α,ω-Diphenylalkanes

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The methylation of α,ω-diphenylalkanes ($C_6H_5(CH_2)_nC_6H_5$, $n = 1-6$) has been performed in the gas phase using $Me_2Cl^+$ ions as alkylating species and toluene as reference substrate. Both in radiolytic experiments at atmospheric pressure and in FT-ICR measurements at $10^{-8}$ Torr, the selected diphenylalkanes reacted faster than toluene, the highest reactivity displayed by 1,3-diphenylpropane. The kinetic pattern of the reaction, conforming to the established scheme of an electrophilic alkylation reaction, is consistent with a rate-determining formation of the $\sigma$-complex intermediate, at variance with the *tert*-butylation of the same series of compounds by $Me_3C^+$ ions, occurring at the collisional encounter rate. The kinetic features are explained by a marked effect due to the presence of the second aryl ring, providing additional stabilization of both the ion−neutral collision complex and the $\sigma$ complex with respect to toluene. Both factors contribute to the $\delta E_a$ of ca. 8 kcal $mol^{-1}$ for the competition of 1,3-diphenylpropane and toluene found in the temperature dependence study of the $Me_2Cl^+$ reaction.

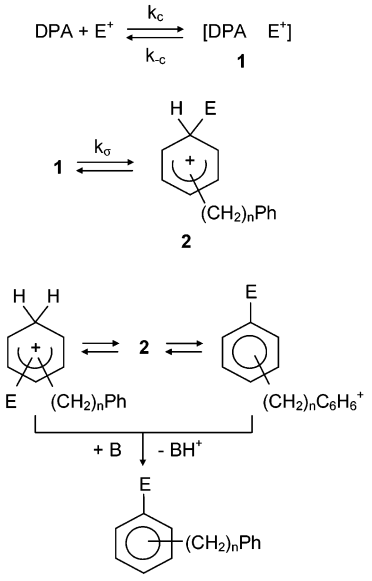
## Introduction

In the general area of noncovalent interactions, the cation−$\pi$ interaction is gaining increasing interest because of many relevant implications in chemistry and biochemistry.[1−4] For example, cation−$\pi$ interactions are found to play a potential role in receptor binding, in enzymatic catalysis, and in the selectivity of ion channels. In the gas phase, the ability of aromatic systems to bind cations forming noncovalent complexes is well-known.[5−13] The two partners, the aromatic system and the cation, however, may also be part of the same molecular network. Recent investigations have focused on the assistance that may be afforded by a "spectator" aromatic $\pi$ system in the course of an ionic reaction.[14−16] The assistance may result from the electrostatic stabilization of transition states and/or ionic intermediates. The gas phase is a medium where ions, lacking any interaction with solvent molecules or counterions, exhibit the foremost request for electrostatic stabilization exploiting any available source to this purpose. The gas phase study of α,ω-diphenylalkanes (DPAs) and their ion-moleule reactions appears a suitable approach to find out how a remote ω-phenyl group may affect the reactivity of a phenyl ring. The electrophilic aromatic substitution by gaseous cations ($E^+$), a well characterized process in the gas phase, has been used as benchmark reaction.[15,17] This reaction is known to occur by a multistep sequence outlined in Scheme 1.

The formation of an ion−neutral complex (**1**) is followed by the formation of a covalent bond between $E^+$ and the aromatic ring leading to a $\sigma$ complex (**2**) that may undergo intra- or interannular proton shift processes before being neutralized by a base. Indeed, the alkylation of DPAs by gaseous $Me_3C^+$ ions has shown that the formation of the ion−neutral complex is the rate-determining step of the whole sequence, because of the electrostatic stabilization afforded by two phenyl rings interacting with this alkyl cation.[18] Noteworthy, the occurrence of ring-to-ring proton migrations in the intermediate $\sigma$ complex is a manifestation of the tendency of the second (spectator) phenyl ring to attain a proximate relationship with the charged ring so that proton shifts are allowed to take place.[19]

The $Me_3C^+$ ion is a mild ionic electrophile whose electrophilic attack at an aromatic ring is reversible to a certain extent. The question then rises as to how the general reactivity pattern of Scheme 1 is affected when the alkylation process becomes irreversible. This instance is presented by the aromatic methy-

**SCHEME 1**

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lation effected by dimethylchloronium ions, $Me_2Cl^+$. Dimethylchloronium ions are known to behave as alkylating agents toward gaseous aromatics according to a formal nucleophilic displacement of MeCl by the aromatic $\pi$-electron system.[20,21] The ensuing reactivity patterns have been the topic of benchmark studies in the field of ion/molecule reactions. The temperature dependence of the alkylation rate constants in particular has made clear that even in a high-pressure ion source at ca. 5 Torr the ion/molecule pair, [$Me_2Cl^+$ substrate], in the collision complex does not experience any perturbation by third body collisions and reacts, by taking full advantage of the electrostatic energy released in the ion−neutral interaction, either by dissociating back to the free reagents or by evolving to products.[22] A negative temperature dependence of the rate constant typically arises when the activation barrier leading to products is lower than the energy required for the back dissociation. An effective thermal equilibration of the collision complex with the environment is achieved only at relatively high pressures (>300 Torr), allowing for example the use of Arrhenius plots to extract information about activation barriers.[21]

In a pressure regime safely beyond this limit ($P \approx 1$ atm), radiolytically formed $Me_2Cl^+$ ions have been allowed to react with selected $\alpha,\omega$-diphenylalkanes, namely, 1,1-diphenylmethane (DPM), 1,2-diphenylethane (1,2-DPE), 1,3-diphenylpropane (1,3-DPP), 1,4-diphenylbutane (1,4-DPB), 1,5-diphenylpentane (1,5-DPP), 1,6-diphenylhexane (1,6-DPH), and 1-(3-methylphenyl)-2-phenylethane (P*m*TE). Using this radiolytic approach,[15] the relative inter- and intramolecular selectivities of the methylation reaction are obtained from the pattern of the neutral end products. A kinetic study of the same reactions by FT-ICR has provided related data in a quite different pressure regime, namely, at ca. $10^{-8}$ Torr.

## Experimental Section

**Materials.** Methyl chloride, methyl fluoride, argon, and oxygen were high purity gases from Matheson Gas Products Inc., used without further purification. Other chemicals, such as DPM, 1,2-DPE, and cyclohexanone, were obtained from Aldrich Chemical Co. Samples of 1,3-DPP, 1,4-DPB, 1,5-DPP, 1,6-DPH, and P*m*TE were obtained as previously described.[23]

**Procedure.** The radiolytic experiments were performed by irradiating an appropriately prepared gaseous mixture in a 220 Gammacell (Nuclear Canada Ltd.) to a dose of $2 \times 10^4$ Gy, at the rate of ca. $1 \times 10^4$ Gy $h^{-1}$. The gaseous mixtures were prepared in sealed glass vessels according to standard procedures using a greaseless vacuum line. Once irradiated, the vessels were opened by way of a break seal arm under airtight conditions, and their contents were recovered by repeated condensation cycles at liquid-nitrogen temperature. Methyl acetate was chosen as solvent. The end solution was analyzed by GLC/MS. The columns allowing the separation of the products mixtures were (i) a 50 m × 0.2 mm cross-linked methylsilicone column (PONA column from Hewlett-Packard) and (ii) a 30 m × 0.25 mm poly(ethylene glycol) bonded-phase column. They were mounted on a Hewlett-Packard 5890 gas chromatograph in series with a 5970B mass-selective detector.

The FT-ICR experiments were performed with a Bruker Spectrospin Apex TM 47e mass spectrometer with an external ion source and a cylindrical "infinity" cell within a 4.7 T superconducting magnet. $Me_2Cl^+$ ions were formed from MeCl under chemical ionization conditions at ca. $3 \times 10^{-5}$ Torr in the external ion source and were led into the cell where Ar was pulsed through a magnetic valve to a pressure of ca. $10^{-6}$ Torr. In a 1 s delay time, unreactive collisions with Ar were allowed to occur, removing excess translational energy from $Me_2Cl^+$ ions. These species were then selected by isolation from other ions formed either in the ion source or in the cell by ion ejection techniques, namely, broad-band ejection and low-energy single shots. The ensuing reaction with a selected DPA at a constant pressure around $2 \times 10^{-8}$ Torr was monitored by recording the relative ion abundances at increasing delay times. The exponential decay of the reagent ion intensity allows one to estimate the pseudo-first-order rate constant. The second-order rate constant is obtained by dividing by the substrate pressure. The substrate pressure is the major source of uncertainty (±30%) in the evaluation of the rate constant values. The values are the average of at least three experiments run at different pressures at the room temperature of 25 °C.

## Results

The reactions of radiolytically formed $Me_2Cl^+$ ions with mono- and diarylalkanes are summarized in Table 1. The experiments are run by reacting selected couples of aromatic substrates in competition to each other with the reagent ion under conditions which typically lead to ca. 1% substrate conversion into products. The gaseous mixtures undergoing $\gamma$ radiolysis are made of MeCl as the bulk gas at nearly atmospheric pressure, $O_2$ at ca. 10 Torr used as scavenger of reactive radicals, cyclohexanone used as a base, and the aromatic substrates in exactly known relative amounts. The yields of the products, measured by the overall radiochemical yield, $G_M$, account for the known yield of the reagent ion, $Me_2Cl^+$.[21] In one of the cases, the reagent ion was $Me_2F^+$ obtained from MeF. The $G_M$ values show the expected decrease as the concentration of the basic additive, *c*-$C_6H_{10}O$, is increased, an effect due to the competition of the additive for the reagent ion, confirming the ionic origin of the observed products. The analysis of the product pattern gives both the intramolecular selectivity of the electrophilic attack and the intermolecular selectivity at the temperature of 120 °C unless specifically varied. The relative reactivities are referred to either toluene or 1,2-DPE as the reference substrate. The given $k_1/k_2$ data allow one to establish the following reactivity trend: P*m*TE (13.2) > 1,3-DPP (9.1) > 1,2-DPE (6) ∼ DPM (6) > 1,5-DPP (4.8) ∼ 1,6-DPH (4.8) > 1,4-DPB (4.2) ∼ *m*-xylene (4.3) > toluene (1). Remarkably, the whole series of diphenylalkanes shows higher or similar reactivity with respect to *m*-xylene, which contains an aromatic ring activated by two, rather than one, alkyl substituents in a proper relationship to stabilize a $\sigma$-complex intermediate by ortho and para substitution. The intermolecular selectivity decreases with increasing temperature, as shown by the $k_{1,3-DPP}/k_{toluene}$ ratio varying from 9.2 at 120 °C to 2.6 at 180 °C. Also, increasing the electrophilicity of the reagent ion, i.e., by replacement of $Me_2Cl^+$ by $Me_2F^+$, cancels any substrate discrimination between P*m*TE and toluene. Regarding the isomeric distribution of the methylation products, the major feature that sets apart toluene from the diphenylalkanes is that the ortho/para distribution characterized by $^1/_2$ ortho:$^1/_2$ meta:para ratio of ca. 2.5:1:2 is shifted toward an increased extent of para substitution, typical $^1/_2$ ortho:$^1/_2$ meta:para values being ca. 1:1:5. DPM is an exception, retaining a pronounced ortho/para distribution of methylation products with the lowest fraction of meta isomer formed. It is also noted that the $k_{m-xylene}/k_{toluene}$ ratio is 4.3, whereas $k_{PmTE}/k_{DPE}$ is only 2.2. In both ratios, two substrates are compared differing only for an additional *m*-methyl group on a phenyl ring. Finally, within P*m*TE, the attack at the *m*-tolyl ring is favored by a factor of 2.8 over the methylation at the unsubstituted phenyl ring.

**TABLE 1: Gas Phase Reactions of $Me_2Cl^+$ with Selected Mono- and Diarylalkanes**

| system composition (Torr)[a] | | | | | products (ring methylated substrates) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | products 1 | | | products 2 | | | |
| substrate 1 | substrate 2 | *c*-$C_6H_{10}O$ | MeCl | *T* (°C) | *o* | *m* | *p* | *o* | *m* | *p* | $k_1/k_2$[b] |
| *m*-xylene 1.06 | toluene[c] 1.05 | 0.27 | 630 | 120 | | *d* | | 60 | 20 | 20 | 4.3 |
| DPM 0.38 | toluene 0.36 | 0.22 | 620 | 120 | 60 | 13 | 27 | 56 | 24 | 20 | 6.0 |
| 1,2-DPE 0.28 | toluene 0.52 | 0.30 | 630 | 120 | 18 | 32 | 50 | 58 | 20 | 22 | 6.0 |
| 1,3-DPP 0.93 | toluene 0.97 | 0.46 | 700[e] | 120 | 24 | 26 | 50 | 50 | 28 | 22 | 0.9 |
| 1.3-DPP 1.68 | toluene 0.51 | 0.22 | 690 | 120 | 20 | 21 | 57 | 48 | 27 | 25 | 9.2 |
| 1,3-DPP 1.47 | toluene 0.72 | 0.27 | 650 | 135 | 19 | 23 | 58 | 46 | 31 | 23 | 6.5 |
| 1,3-DPP 1.25 | toluene 0.65 | 0.30 | 610 | 150 | 20 | 22 | 58 | 44 | 33 | 23 | 4.4 |
| 1,3-DPP 3.15 | toluene 1.82 | 0.66 | 600 | 180 | 25 | 22 | 53 | 40 | 37 | 23 | 2.6 |
| DPM 0.53 | 1,2-DPE 0.30 | 0.36 | 610 | 120 | 62 | 12 | 26 | | 20 | 28 | 0.9 |
| 1,3-DPP 0.29 | 1,2-DPE 0.32 | 0.34 | 660 | 120 | 20 | 21 | 59 | 20 | 28 | 52 | 1.5 |
| P*m*TE 0.49 | 1,2-DPE 0.52 | 0.34 | 660 | 120 | 20 | 30 | 50[f] | 17 | 27 | 56 | 2.2 |
| 1,4-DPB 0.20 | 1,2-DPE 0.31 | 0.21 | 600 | 120 | 26 | 20 | 54 | 18 | 28 | 54 | 0.7 |
| 1,5-DPP 0.23 | 1,2-DPE 0.26 | 0.27 | 630 | 120 | 28 | 21 | 51 | 19 | 28 | 53 | 0.8 |
| 1.6-DPH 0.12 | 1,2-DPE 0.23 | 0.21 | 600 | 120 | 26 | 21 | 53 | 19 | 27 | 54 | 0.8 |

[a] $O_2$ (10 Torr) was present in all gaseous systems. [b] $k_1/k_2$was obtained from the ratio of the yields of the methylated products 1 ($P_1$) and 2 ($P_2$) normalized by the ratio of the reagent substrates 1 ($S_1$) and 2 ($S_2$). $k_1/k_2 = ([P_1]/[P_2]) \times ([S_2]/[S_1])$. [c] Toluene-$d_8$ was used in order to discriminate between its *m*-methylation product and unlabeled *m*-xylene, the competing substrate 1. [d] The methylation products of *m*-xylene were formed in the following % ratio: 1,3,5-trimethylbenzene (5%), 1,2,4-trimethylbenzene (62%), 1,2,3-trimethylbenzene (33%). [e] MeF was used in the place of MeCl (reagent ion $Me_2F^+$). [f] The given % distribution refers to the methylation products of the unsubstituted ring of P*m*TE. The methylation products at the *m*-tolyl ring are as follows: 1-(2,3-dimethylphenyl)-2-phenylethane (38%), 1-(3,4-dimethylphenyl)-2-phenylethane (49%), 1-(3,5-dimethylphenyl)-2-phenylethane (13%). The products of methylation at the *m*-tolyl and at the phenyl ring are formed in an overall ratio of 2.8.

**TABLE 2: FT-ICR Rate Constants for the $Me_2Cl^+$ Reaction with Selected Mono- and Diarylalkanes**

| substrate | $k$[a] | efficiency[b] | products *m*/*z* |
|---|---|---|---|
| toluene | 0.05 | 0.03 | 107 ($Me_2C_6H_5^+$) |
| DPM | 0.5 | 0.32 | 91 ($PhCH_2^+$), 105 ($MeC_6H_4CH_2^+$) |
| 1,2-DPE | 0.5 | 0.30 | 105 ($PhC_2H_4^+$), 119 ($MeC_6H_4C_2H_4^+$) |
| P*m*TE | 2.0 | 1.0 | 105 ($PhC_2H_4^+$), 119 ($MeC_6H_4C_2H_4^+$) 133 ($Me_2C_6H_3C_2H_4^+$)[c] |
| 1,3-DPP | 1.9 | 1.0 | 211 ($Ph(CH_2)_3C_6H_5Me^+$)[d] |

[a] Phenomenological rate constants in units of $10^{-9}$ cm$^3$ molecule$^{-1}$ s$^{-1}$. [b] Efficiency $= k/k_c$, where the collisional rate constant $k_c$ has been calculated according to ref 24. [c] The ratio ([*m*/*z* 105] + [*m*/*z* 133])/[*m*/*z* 119] is constant at initial reaction times ($t = 0.3-2.1$ s) and equal to 2.9. [d] Only traces of fragment ions at *m*/*z* 105 and *m*/*z* 119 are observed.

The relative reactivities obtained by the competition experiments run in radiolytic systems at atmospheric pressure have been compared with the absolute rate data that are obtained from the kinetic study of the methylation reaction by FT-ICR spectrometry. The second order rate constants are reported in Table 2 together with the reaction efficiencies, which reflect the fraction of collision events leading to products. Once again, a clearly distinct behavior is found for toluene, showing a 0.03 reaction efficiency, and for the diphenylalkanes, showing a reaction efficiency varying between 0.3 and 1.0. The reaction products are characterized by their *m*/*z* values together with an assignment of their plausible constitution.[14] At variance with toluene and 1,3-DPP, which yield the methylated ion as the only or by far the predominant species, the other DPAs that were investigated give product ions resulting from the fragmentation by loss of an arene molecule from the primary methylated species. Scheme 2 describes the possible processes activated by the methylation of P*m*TE. Whereas ions with *m*/*z* 105 and *m*/*z* 133 are formed via the intermediate $\sigma$ complex methylated at the *m*-tolyl ring, ions with *m*/*z* 119 are obtained from the methylation of the phenyl ring of P*m*TE. Therefore, the ratio of the respective ion abundances, viz. ([*m*/*z* 105] + [*m*/*z* 133])/[*m*/*z* 119], represents the branching of the electrophilic attack at the two $\pi$ systems. Interestingly, the abundance ratio ([*m*/*z* 105] + [*m*/*z* 133])/[*m*/*z* 119] = 2.9 (cf. footnote c to Table 2) is close to the branching found for the radiolytic methylation.

## Discussion

It is convenient to start a discussion comparing the reactivity behavior of the two reagents, $Me_2Cl^+$ and $Me_3C^+$. The radiolytic methylation of the selected DPAs displays a reactivity pattern that stands in contrast with the one obtained for the radiolytic *tert*-butylation of the same substrates.[18] $Me_3C^+$ has been reported to alkylate DPAs with little or no substrate selectivity as shown by the relative reactivities at 120 °C listed in Table 3. At the same time, a sizable intramolecular selectivity characterizes the *tert*-butylation of P*m*TE where the activated *m*-tolyl ring is favored by a factor of 2.2 over the unsubstituted phenyl ring. This evidence and the study of H/D kinetic isotope effects concurred to assign the observed reactivity pattern to a rate-determining formation of the collision complex **1**. Complex **1** evolves into the $\sigma$-complex **2** in a reversible process character-

**SCHEME 2**

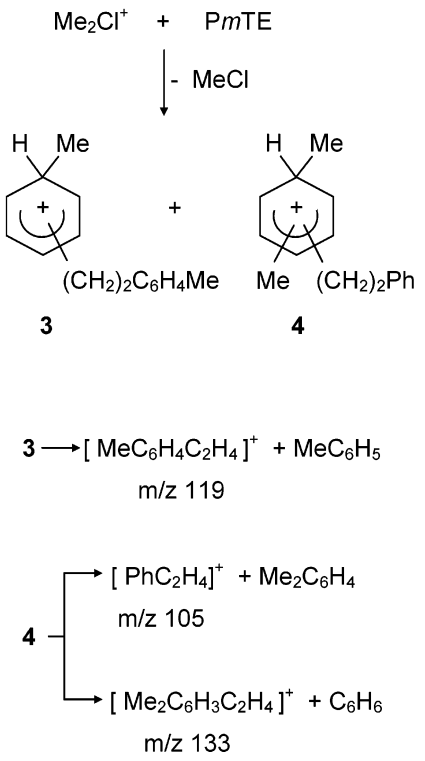


**TABLE 3: Relative Reactivities for the Reaction of Alkylating Cations with Selected Mono- and Diphenylalkanes**

| substrate (GB)[a] | $Me_3C^+$ [b] | $Me_2Cl^+$ [c] | $Me_2Cl^+$ [d] |
|---|---|---|---|
| toluene (180.8) | 1 | 1 | 1 |
| *m*-xylene (187.9) | | 4.3 | |
| DPM (184.5) | 2 | 6 | 10 |
| 1,2-DPE (185.8) | 4.5 | 6 | 10 |
| 1,3-DPP (188.4) | 4.5 | 9.1 | 30 |
| 1,4-DPB (186.4) | 4.5 | 4.2 | |
| 1,5-DPP (187.5) | | 4.8 | |
| 1,6-DPH (188.0) | | 4.8 | |
| P*m*TE (191.1) | 4.5 | 13 | 30 |

[a] Gas-phase basicity (GB, kcal $mol^{-1}$) values are from ref 25 (toluene and *m*-xylene) and ref 26 (DPAs). [b] Radiolysis at 120 °C, ref 18. [c] Radiolysis at 120 °C, this work. [d] ICR, this work.

ized by a low activation barrier. The reversibility of the process was inferred from the distinct intramolecular selectivity in the *tert*-butylation of P*m*TE as well as from the discrimination in the formation of substitution products at the deuterated vs unlabeled ring of $C_6H_5(CH)_2C_6D_5$. Once again, the intermolecular competition between $C_6D_5(CH)_2C_6D_5$ and DPE did not show any isotope effect. The mechanism suggested to account for the observed reactivity can be explained by the low activation barrier for the formation of **2** making this process fast with respect to the back dissociation of **1** into the free reactants. The dissociation is furthermore contrasted by the stabilization provided by the two aryl rings interacting with $Me_3C^+$ within the collision complex, a prominent difference with toluene. Toluene, chosen as reference aromatic substrate, is otherwise predicted to be similar to DPAs with respect to activation toward electrophilic addition, because of the close $\sigma_p^+$ values (for example −0.31 for the Me group and −0.265 for $PhCH_2CH_2$).[27]

The methylation reaction by $Me_2Cl^+$ can be presented within the framework of Scheme 1 if one recognizes that the addition of $E^+ = Me^+$ to the aromatic ring is accompanied by cleavage of MeCl, in other words the alkylation is a methyl transfer process rather than a simple addition reaction. As shown in Table 3, the relative reactivities of the electrophilic methylation are clearly dependent on the features of the DPA substrates, notably the length of the aliphatic chain and the presence of a methyl substituent at an aryl ring. This finding points to the formation of the $\sigma$-complex **2** as the rate-determining step of the methylation reaction because the $k_c$ rate constant, depending on parameters such as the dipole moment and polarizability of the neutral,[24] is expected to be closely similar for all of the members of the DPA series. This point is further confirmed by the intermolecular selectivity for the methylation of P*m*TE and 1,2-DPE ($k_{PmTE}/k_{1,2-DPE} = 2.2$) which parallels the intramolecular selectivity between the methylated and unsubstituted rings of P*m*TE ($k_{\sigma,m-tolyl}/k_{\sigma,phenyl} = 2.8$). On a quantitative basis, the two selectivities match very well with the model of a fast preequilibrium for the formation of **1**, with P*m*TE and 1,2-DPE reasonably sharing the same constant $K_c$, preceding the rate determining formation of **2**. The rate constant for the latter step is a combination of $k_{\sigma,m-tolyl}$ and $k_{\sigma,phenyl}$ in the case of P*m*TE ($k_\sigma = k_{\sigma,m-tolyl} + k_{\sigma,phenyl}$) and would be equal to $2k_{\sigma,phenyl}$ ($k_\sigma = 2k_{\sigma,phenyl}$) in the case of 1,2-DPE. Under the foregoing assumptions, the $k_{PmTE}/k_{1,2-DPE}$ ratio is given by the ratio of eqs 1 and 2, yielding an expected value of 1.9. The only slightly higher experimental ratio is consistent with the mechanistic model and suggests that P*m*TE may be somewhat favored in the association of $Me_2Cl^+$ with respect to 1,2-DPE

$$k_{PmTE} = K_c(k_{\sigma,m-tolyl} + k_{\sigma,phenyl}) \quad (1)$$

$$k_{1,2-DPE} = 2K_c k_{\sigma,phenyl} \quad (2)$$

Because the rate constant for the methylation of DPAs by $Me_2Cl^+$ ions includes the contribution of both the equilibrium constant for the association of the reagents and the rate constant for the electrophilic attack forming **2**, it would be desirable to ascertain their relative importance in determining the markedly higher reactivity of DPAs with respect to toluene. The different reactivity cannot be explained by electronic activation effects, which are expected to be similar. The dependence of the activation effect on the length of the aliphatic chain, favoring the radiolytic methylation of 1,3-DPP over the lower and higher homologues, underlines the role played by the second phenyl ring. The presence of this group may affect the stability of both the collision complex **1**, where $Me_2Cl^+$ can gain electrostatic stabilization by the interaction with two aromatic rings rather than only one, and the $\sigma$-complex **2**, where the "spectator" aryl group may approach and stabilize the arenium ion. In both cases, the length of the aliphatic chain will affect the proximate relationship that may be attained between the electron donor(s) and the cationic moiety. It is not easy to estimate these effects on a quantitative basis, also because their relative weight may vary from one member to the next in the DPA series. The positive effect in stabilizing **1** against dissociation is clear in the higher reactivity of $Me_2Cl^+$ with DPAs relative to toluene in the methylations run by FT-ICR. Whereas one typically observes a decrease in the intermolecular selectivity of an ion−molecule reaction when radiolytic results at nearly atmospheric pressure are compared to kinetic data obtained at ca. $10^{-8}$ Torr by FT-ICR, an opposite behavior is clearly shown by the relative reactivities summarized in Table 3. This behavior is ascribed to the increased lifetime of the [$Me_2Cl^+$ DPA] collision complex allowed by the presence of the two phenyl rings. The toluene complex, lacking the second aryl group, is exceedingly short-lived in FT-ICR where the low pressure (ca $10^{-8}$ Torr) prevents

an efficient collisional stabilization of excited ion−molecule complexes.[28] Because of the shortened lifetime of its collision complex with $Me_2Cl^+$, toluene appears less prone to undergo methylation. In the radiolytic methylations at atmospheric pressure, the collision complex undergoes frequent unreactive collisions with molecules of the bath gas removing the energy released in the ion−neutral encounter and may thus reach thermal equilibrium with the environment. The simultaneous coordination of the electrophile with both aryl rings of a DPA within **1**, involving regions of $\pi$-electron density farther from the junction of the (poly)methylene chain, will favor methylation at the para rather than ortho position. This effect has been suggested to account for the unusually low fraction of ortho methylation in the $Me_2Cl^+$ reaction with DPE.[29] In this work, comparing a series of DPAs, the low fraction of ortho methylation is found to be a common feature, with the only exception of DPM, which shows a positional selectivity similar to that of toluene.

To understand the effect of the spectator ring in the formation of **2**, it is useful to refer to the thermodynamic parameters for the protonation of DPAs also listed in Table 3 as the gas phase basicity (GB) values. The structure dependence of the GBs for the DPA series with increasing number of methylene units shows that protonated 1,3-DPP is stabilized with respect to the close homologues, 1,2-DPE and 1,4-DPB. The unexpectedly high basicity of 1,3-DPP has been ascribed to the favorable conformation allowed to the protonated species where a parallel arrangement of the protonated and spectator ring can maximize the electrostatic stabilization of the positive charge.[26] In protonated 1,3-DPP, this conformation is compatible with an all-staggered conformation of the methylene chain. The same trend, favoring 1,3-DPP over both 1,2-DPE and 1,4-DPB, is displayed by the radiolytic reaction of $Me_2Cl^+$, consistent with the fact that the incipient formation of the methylated arenium ion should share features of the protonated species, approaching a $\sigma$-complex structure. Another, probably more striking, piece of evidence regarding the stabilization imparted by the spectator ring on the forming arenium ions from DPAs comes from the product pattern of the FT-ICR methylation. At variance with other members of the series, 1,3-DPP is the only homologue from which the methylated ion is formed as the major product. Noteworthy, this species is stable against the dissociation by loss of an arene molecule, the common process for the lower homologues and, in general, the by far most facile pathway for the unimolecular fragmentation of protonated DPA's und related hydrocarbons.[14,19]

The temperature dependence of the radiolytic methylation of 1,3-DPP vs toluene has been investigated in the temperature range of 120−180 °C. The ensuing relative reactivity data (Table 1) are presented in the Arrhenius plot of Figure 1, showing that the difference in the reactivity of the two substrates is reduced as the temperature increases. The slope of the straight line is related to the difference of activation energy for the methylation of the two compounds, yielding $E^a_{toluene} - E^a_{1,3-DPP} = 7.7$ kcal mol$^{-1}$. Once again, because the rate constant for the methylation reaction is a combination of the equilibrium constant for the association of the reagents and the rate constant for the formation of the $\sigma$ complex ($K_c k_\sigma$), the difference of activation energy is made of a $\delta\Delta H^\circ_c$ term, accounting for the difference in $\Delta H^\circ_c$ for the association of $Me_2Cl^+$ with toluene and 1,3-DPP, and a $\delta E^a_\sigma$ term, equal to the difference in activation energy for the formation of the methylated $\sigma$ complex of toluene and 1,3-DPP. Both contributions are expected to be positive because of the stabilizing influence of the additional aryl group of 1,3-DPP making $\Delta H^\circ_c$ more negative and $E^\sigma_a$ lower with respect to toluene. A quantitative evaluation could be possible from the knowledge, not presently available, of $\Delta H^\circ_c$ for the association of $Me_2Cl^+$ with 1,3-DPP. The association equilibrium between $Me_2Cl^+$ and toluene is characterized by $\Delta H^\circ_c = -12.2$ kcal mol$^{-1}$ as reported by a high-pressure mass spectrometric study.[22]

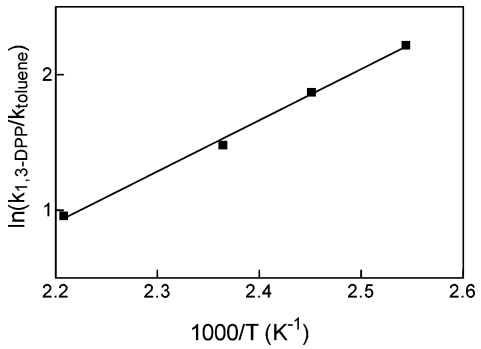


**Figure 1.** Temperature dependence of the $k_{1,3-DPP}/k_{toluene}$ ratio for the competitive methylation of 1,3-DPP and toluene by gaseous $Me_2Cl^+$ ions in MeCl at atmospheric pressure.

Finally, but still referring to Scheme 1, the formation of **2** can be followed by interannular hydrogen shifts that have been proven and studied by the radiolytic approach in the $Me_2Cl^+$ and $Me_3C^+$ reactions with DPE.[30] However, they do not appear to affect the overall reaction kinetics studied in the present work.

## Conclusions

$Me_2Cl^+$ and $Me_3C^+$ are quite different electrophiles and so is their reactivity behavior toward aromatic systems in the gas phase. The former species is a methylating agent by a nucleophilic displacement process where the aromatic ring acts as the nucleophile displacing MeCl while forming a methylated $\sigma$ complex. The formation of the $\sigma$ complex is irreversible for this highly exothermic process involving the simultaneous departure of a MeCl molecule. For example, an exothermicity of more than 20 kcal mol$^{-1}$ can be estimated for the methylation of benzene by $Me_2Cl^+$ ions, based on a value of 59 kcal mol$^{-1}$ for the methyl cation affinity of MeCl[31] and on a recently calculated value of 81 kcal mol$^{-1}$ for benzene.[32] At the same time, the methylation involves a substantial activation energy,[21,22] making the $\sigma$-bond formation slow with respect to the dissociation of **1** to the free reactants. In contrast with the $Me_2Cl^+$ reaction, the $Me_3C^+$ addition to an aromatic ring is close to thermoneutral and reversible.[12,33] However, the addition of this carbocation to the $\pi$ system appears to be fast relative to the back dissociation process. Within the framework of Scheme 1, changing the electrophile from $Me_3C^+$ to $Me_2Cl^+$ causes a change in the kinetic pattern from a rate-determining collisional encounter forming **1** to a rate-determining formation of the $\sigma$-complex **2**.

The common feature of the $Me_2Cl^+$ and $Me_3C^+$ reactions with DPAs was found to be the role of the additional aryl ring that makes the reactivity behavior of these substrates quite distinct from that of toluene. The presence of the second aryl ring affects the stability of the collision complex **1**, making it longer lived, and exerts a stabilizing influence also on the arenium ion **2** where the positively charged ring can be approached by the spectator ring through an appropriate folding of the (poly)methylene chain. Both effects conceivably contribute to the difference in overall activation energy for the $Me_2Cl^+$ reaction with 1,3-DPP and toluene, amounting to ca. 8 kcal mol$^{-1}$. 1,3-DPP results to be the most reactive among the tested DPAs, in agreement with its highest GB in the same series.

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