

# Relationship between local electrophilicity and rate coefficients for the hydrolysis of carbenium ions

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**Abstract**—The local electrophilicity of a series of 28 carbenium ions has been ranked within a theoretical absolute scale. New substituent constants are introduced to account for the responses of the electrophilicity pattern induced by multiple substitutions at the carbocation site. The model is used to predict rate coefficients ordering in terms of the experimental hierarchy of electrophilicity established for these systems [Minegishi, S.; Mayr, H. *J. Am. Chem. Soc.* **2003**, *125*, 286].

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## 1. Introduction

After the introduction of the concepts of electrophilicity and nucleophilicity by Ingold<sup>1</sup> in the 1930s, there has been a growing interest in classifying atoms and molecules within empirical scales of electrophilicity/nucleophilicity. The main idea behind this objective has been the search of absolute scales that could be independent on the reactivity of the nucleophile/electrophile partners. This objective is ambitious if one considers that a universal scale should accommodate a wide diversity of chemical species presenting quite different structural and bonding properties. For instance, one of the first attempts to classify electron donors within a single nucleophilicity scale was reported by Swain and Scott,<sup>2</sup> who defined a nucleophilicity number as an intrinsic property of nucleophiles, using rate coefficients for a series of S<sub>N</sub>2 reactions. Other attempts to quantitatively rank the nucleophilic power of molecules were proposed by Edwards, using a four parameter scheme,<sup>3</sup> and by Edwards and Pearson<sup>4</sup> using the hard and soft acids and bases (HSAB) empirical rule.

Recently, Mayr et al. in a series of articles persuasively argued in favour of nucleophilicity and electrophilicity parameters that are independent of the reaction partner.<sup>5–10</sup> They proposed that the rate coefficients for the reactions of

carbocations with uncharged nucleophiles obey the linear free energy relationship:

$$\log k = s(E + N) \quad (1)$$

where  $E$  and  $N$  are the electrophilicity and nucleophilicity parameters, respectively, and  $s$  is the nucleophilic-specific slope parameter. This sensitivity parameter is usually close to unity, so that it may be neglected for the purpose of qualitative comparisons. These authors have clearly emphasized and illustrated the usefulness of the nucleophilicity/electrophilicity scales to quantitatively discuss reactivity as well as inter molecular selectivity.<sup>5–10</sup>

From a theoretical point of view, the electrophilicity concept has attracted the attention of several authors.<sup>11–15</sup> Most of the proposed definitions of electrophilicity are framed on reactivity indexes. By construction, the theoretical scales of electrophilicity, based on descriptors of the electronic structure defined at the ground state of molecules (i.e., static reactivity indexes) are absolute scales, in the sense that they are independent on the nucleophile partners. On the other hand, a quantitative definition of nucleophilicity in terms of electronic reactivity indexes turned out to be a more difficult task, and few attempts to quantitatively define nucleophilicity within this framework have been reported to date. The Fukui function based *philicity* index introduced by Chattaraj et al.<sup>16</sup> and the nucleophilicity index defined from vertical ionization potentials<sup>17</sup> are among the few efforts devoted to this subject.

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*Keywords:* Hammett substituent constants; Local electrophilicity scale; Rate coefficients from local electrophilicity index.

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Validated theoretical scales of electrophilicity/nucleophilicity are highly desirable, as they can further provide valuable information about the intramolecular selectivity. In this article, we present a quantitative classification of the electrophilicity pattern for a series of 28 carbenium ions, using the global electrophilicity index introduced by Parr et al.,<sup>12</sup> and a local extension condensed to atom or functional groups.<sup>18</sup> The local contribution incorporates the electrophilic Fukui function to regionally project the global electrophilicity of these charged electron acceptors. From the knowledge of the electrophilicity index at the carbocation site, accurate rate coefficients may be predicted.

## 2. The model

The concept of electrophilicity viewed as a reactivity index was introduced rather recently by Parr et al.<sup>12</sup> It is based on a second order expansion of the electronic energy with respect to the charge transfer  $\Delta N$  at fixed geometry. Since electrophiles are species that stabilize upon receiving an additional amount of electronic charge from the environment, there exist a minimum of energy for a particular  $\Delta N^*$  value. Using this simple idea, Parr et al. performed a variational calculation that led to the definition of the global electrophilicity index as  $\omega = -\Delta E(\Delta N^*)$ , which may be recast into the more familiar form:<sup>12</sup>

$$\omega = \frac{\mu^2}{2\eta}; \quad (2)$$

in terms of the electronic chemical potential  $\mu$  and the chemical hardness  $\eta$ . The  $\omega$  index establishes an absolute scale of electrophilicity in the sense that the hierarchy of electrophilicity is built up from the electronic structure of molecules, independent of the nucleophilic partner, which is replaced by an unspecified environment viewed as sea of electrons.<sup>12</sup>

Beside the global electrophilicity index, it is possible to define its local (or regional) counterpart condensed to atoms. The local electrophilicity index  $\omega_k$  condensed to atom  $k$  is easily obtained by projecting the global quantity onto any atomic center  $k$  in the molecule by using the electrophilic Fukui function (i.e., the Fukui function for nucleophilic attack,  $f_k^+$ ). There results:<sup>18</sup>

$$\omega_k = f_k^+ \omega \quad (3)$$

The regional or condensed to atom electrophilicity index has been shown to correctly assess the regioselectivity in a number of cases.<sup>18–20</sup> In summary, while the global electrophilicity index categorizes within a unique scale the electron acceptor ability of molecules, its local or regional counterpart plays a key role in the elucidation of the intramolecular selectivity of the same systems. Note that site electrophilic activation may also be assessed as the variation in local electrophilicity induced for instance by chemical substitution or any source of external perturbation to the molecular system.

## 3. Computational details

All the structures included in this study were optimized at the B3LYP/6-31G(d) level of theory using the Gaussian98 package of programs.<sup>21</sup> The values of the electronic chemical potential and the chemical hardness were obtained from the expressions  $\mu \approx (\varepsilon_H + \varepsilon_L)/2$  and  $\eta \approx \varepsilon_L - \varepsilon_H$ , in terms of the one electron energies of the HOMO and LUMO frontier molecular orbitals,  $\varepsilon_H$  and  $\varepsilon_L$ , respectively.<sup>22</sup> With these quantities at hand, the global electrophilicity was obtained using Eq. (2). The local electrophilicity values were obtained from the global electrophilicity index and the electrophilic Fukui function using Eq. (3). The electrophilic Fukui function was evaluated from a single point calculation in terms of the molecular orbital coefficients and the overlap matrix using a procedure described elsewhere.<sup>23,24</sup>

## 4. Results and discussion

The systems considered in the present study are depicted in Chart 1. Included in these series are the tritylium, benzhydrylium, and benzylium ions. In order to set up the appropriate scenario to discuss the electrophilicity pattern of these systems, let us mention that, for instance, the neutral electrophilic species participating in Diels–Alder reactions (i.e., the dienophiles) present local electrophilicity numbers in the range 1.14 eV (acrolein–BH<sub>3</sub> complex) to 0.10 eV (dimethylvinylamine) within the theoretical scale.<sup>18</sup> As expected, the electron deficient carbenium ions display an even higher local electrophilicity range comprised between [2.0–6.0] eV (see fourth column of Table 1 and Chart 2).

Figure 1 summarizes the comparison between the local electrophilicity index evaluated at the carbocation site,  $\omega_C$ , and the logarithm of the rate coefficient for the hydrolysis for the whole series of 28 carbenium ions depicted in Chart 1. The resulting regression equation is:

$$\text{Log } k_w = 4.714 \omega_C - 13.827. \quad (4)$$

The linear relationship between both variables is qualitatively acceptable (regression coefficient  $R \approx 0.94$ ) if one considers that this series of carbenium ions comprises a large variety of different structures, thereby suggesting that the regional electrophilicity patterns at a carbocation site, imbedded in different chemical environments may be used to correctly assess the effect of chemical substitution on the electrophilic potential of molecules, and therefore it can be further considered as a reliable descriptor of reactivity. The deviations of compounds 21, 22, 23 that show the highest values of electrophilicity at the carbocation site may be at least partially due to the fact that the rate constants of these compounds with water are close to the diffusion control limit. For this reason the increase of  $\omega_C$  cannot be reflected in these rate constants.<sup>25</sup>

Despite the deviations observed, we may still validate the linear relationship given in Eq. (4) by using it to predict the rate coefficient for the neutral hydrolysis of other carbenium ions not included in the present data base. An immediate application of Eq. (4) is the evaluation of the rate coefficient for the *p*-CH<sub>3</sub> tritylium ion not included in the regression

Carbenium ions	R <sub>1</sub>	R <sub>2</sub>	R <sub>3</sub>	$\sigma_p(\omega_C)$	Carbenium ions	R <sub>1</sub>	R <sub>2</sub>	R <sub>3</sub>	$\sigma_p(\omega_C)$
1				0.01	15	H			-0.11
2				-0.34	16	H			-0.81
3				-0.68	17	H			-1.13
4				-0.81	18	H			-1.15
5				-1.05	19	H			-1.36
6				-1.07	20	H			-1.36
7				-1.35	21	CH <sub>3</sub>		H	2.89
8				-1.31	22	CH <sub>3</sub>		CH <sub>3</sub>	2.35
9				-1.92	23	CH <sub>3</sub>		H	1.90
10	H			1.14	24	H		H	1.35
11	H			0.82	25	CH <sub>3</sub>		H	1.08
12	H			0.56	26	H		OCH <sub>3</sub>	1.17
13	H			0.35	27	CH <sub>3</sub>		OCH <sub>3</sub>	0.64
14	H			0.16	28	CH <sub>3</sub>		OCH <sub>3</sub>	-0.21

**Chart 1.** Carbenium ions considered in the present study and substituent constants for multiple substitutions.

**Table 1.** Global electrophilicity ( $\omega$ ), electrophilic Fukui function at the carbocation site ( $f_C^+$ ), local electrophilicity at the carbocation site ( $\omega_C$ ) and log of the rate coefficients for hydrolysis of carbenium ions,  $k_w^{a,b}$

Carbenium ions	$\omega$ [eV]	$f_C^+$	$\omega_C$ [eV]	Log $k_w$ [s <sup>-1</sup> ]
1	11.1	0.3363	3.72	5.18
2	10.7	0.3207	3.44	3.00
3	10.2	0.3105	3.17	1.98
4	10.1	0.3015	3.07	-2.02
5	9.7	0.2956	2.88	-2.34
6	9.4	0.3044	2.86	1.17
7	9.3	0.2853	2.64	-3.68
8	9.1	0.2924	2.67	-2.64
9	7.9	0.2781	2.19	-4.71
10	13.0	0.3550	4.61	8.48
11	12.6	0.3456	4.36	8.08
12	12.3	0.3376	4.15	7.51
13	12.1	0.3311	3.99	6.32
14	11.8	0.3252	3.84	5.96
15	11.5	0.3161	3.62	5.11
16	10.6	0.2903	3.07	0.58 <sup>b</sup>
17	10.1	0.2790	2.81	-0.48 <sup>b</sup>
18	9.9	0.2845	2.80	-1.59 <sup>b</sup>
19	9.4	0.2845	2.63	-2.25 <sup>b</sup>
20	9.4	0.2799	2.63	-2.66 <sup>b</sup>
21	13.7	0.4376	6.00	11.00
22	12.8	0.4358	5.57	10.23
23	12.5	0.4172	5.22	9.60
24	12.2	0.3925	4.78	8.30
25	11.6	0.3948	4.57	7.70
26	11.2	0.4163	4.64	9.30
27	10.4	0.4054	4.22	7.70
28	9.5	0.3743	3.54	6.85

<sup>a</sup> Log  $k_w$  values from Refs. 5, 7 and 26.

<sup>b</sup> Log  $k_w$  values from Ref. 9.

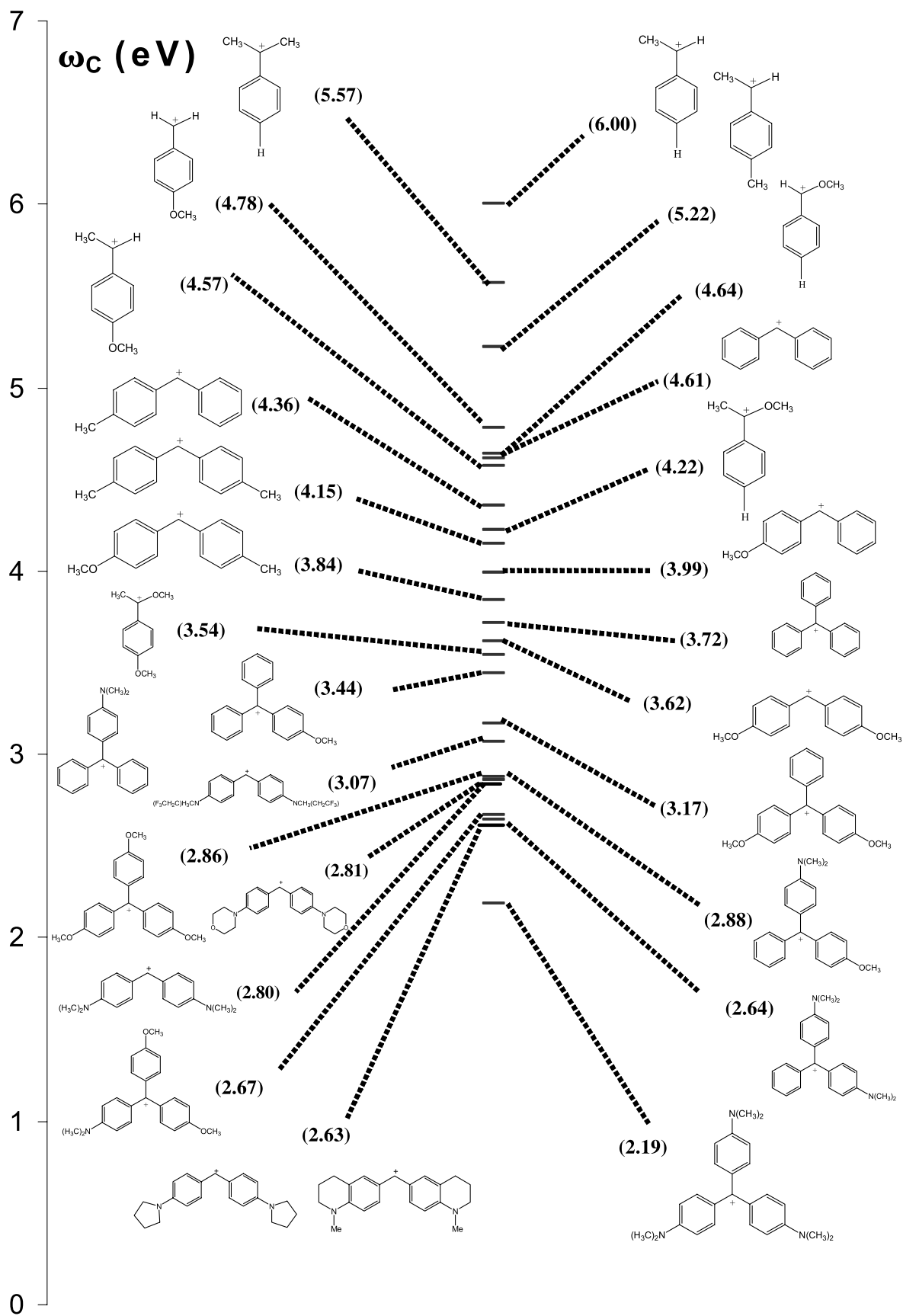
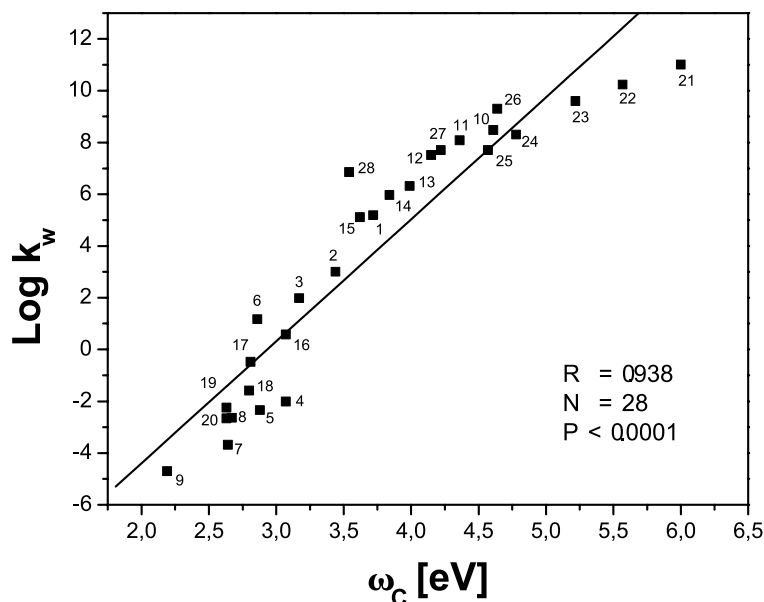


Chart 2. Local electrophilicity scale for carbenium ions.

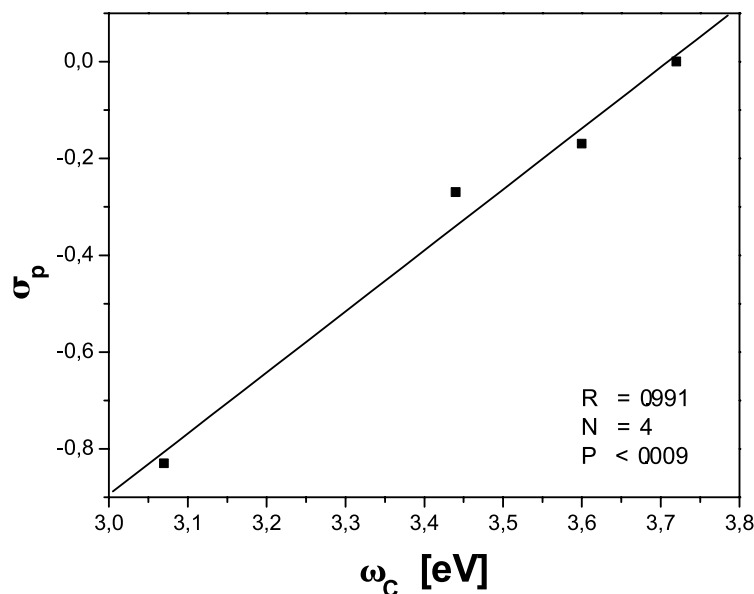


**Figure 1.** Comparison between experimental  $\log k_w$  for the neutral hydrolysis of 28 carbenium ions and the local electrophilicity index at the carbocation site,  $\omega_C$ .  $R$  is the regression coefficient;  $N$  is the number of points and  $P$  is the probability that the observed correlation was randomly obtained.

analysis shown in Figure 1, for which  $\omega_C = 3.60$  eV. Application of Eq. (4) to this compound yields a predicted  $\log k_w = 3.14$ . The experimental electrophilicity parameter ( $E = -0.13$ ) for this compound has been recently reported by Mayr and Minegishi.<sup>9</sup> It is upper bounded by the  $E$  parameter for tritylium ion ( $E = 0.51$ ,  $\log k_w = 5.18$ , compound **1** in Table 1), and lower bounded by ( $p$ -OCH<sub>3</sub> tritylium ion ( $E = -1.87$ ,  $\log k_w = 3.00$ , compound **2** in Table 1). Since the  $E$  parameter shows a linear relationship with  $\log k_w$ ,<sup>8</sup> the order relationship  $\log k_w$  ( $p$ -OCH<sub>3</sub> tritylium ion)  $<$   $\log k_w$  ( $p$ -CH<sub>3</sub> tritylium ion)  $<$   $\log k_w$  (tritylium ion) is also satisfied. Another pertinent prediction concerns the rate coefficient for the hydrolysis of the tris- ( $o,p$ -OCH<sub>3</sub>)<sub>2</sub> tritylium ion experimentally evaluated by Ritchie<sup>26</sup> and not included in the present database. Using its

local electrophilicity value  $\omega_C = 2.65$  eV, the predicted rate coefficient obtained from Eq. (4) yields  $\log k_w = -1.33$  which is again correctly upper and lower bounded by those of tritylium ion ( $\log k_w = 5.18$ , compound **1** in Table 1) and ( $p$ -N(Me)<sub>2</sub>,  $p$ -OCH<sub>3</sub>) tritylium ion ( $\log k_w = -2.34$ , compound **5** in Table 1).

The analysis of the effect that the different substituents may have on the rate coefficients in this case is particularly hard to perform by using simple inductive effects, as described for instance by the Hammett substituent constants. Note that, despite the fact that most of the 28 carbenium ions exhibit *para*-substitution, the general structure on top of Chart 1, shows a complex substitution pattern at the carbocation centre. In order to assess the effect of multiple



**Figure 2.** Comparison between Hammett substituent  $\sigma_p$  constants for singly substituted carbenium ions and the local electrophilicity index  $\omega_C$ .  $R$  is the regression coefficient;  $N$  is the number of points and  $P$  is the probability that the observed correlation was randomly obtained.

substitution at this site, we first considered those compounds that have two fixed hydrogen atoms at the *p*-position of the phenyl group, which according to Hammett classification have  $\sigma_p(\text{H})=0.0$ , and the third phenyl group substituted at *p*-position with H (compound **1** in Chart 1),  $\text{OCH}_3$  (compound **2** in Chart 1),  $\text{N}(\text{Me})_2$  (compound **4** in Chart 1), plus the *p*- $\text{CH}_3$  substituted compound not shown in Chart 1 (for which  $\omega_C=3.60$  eV). The comparison between the  $\sigma_p$  values and the local electrophilicity index  $\omega_C$  is shown in Figure 2. It may be seen that for this short series the  $\sigma_p$  increases linearly with the local electrophilicity index  $\omega_C$  (regression coefficient  $R\approx 0.99$ ). The resulting empirical equation is:

$$\sigma_p = 1.261\omega_C - 4.676. \quad (5)$$

From this equation, we define a new substituent constant  $\sigma_p(\omega_C)$  which is uniquely determined by the knowledge of the  $\omega_C$  index. The  $\sigma_p(\omega_C)$  values for the whole series of carbenium ions considered in this work are shown in Chart 1, last column. The following results are relevant: in the tritylium subseries (compounds **1–9** in Chart 1), multiple substitution at the carbocation site with *p*- $\text{OCH}_3$  and *p*- $\text{N}(\text{Me})_2$  substituted phenyl groups results in an electrophilic deactivation ( $\sigma_p(\omega_C)<0$ ), thereby indicating that the net effect of these groups is to act as electron releasing substituents. Note that the rate coefficients are consistently predicted to be less than the reference compound **1** (see Table 1). While the  $-\text{OCH}_3$  group seems to make an approximately additive contribution to  $\sigma_p(\omega_C)$  of *c.a.* 0.34 units, in the case of increasing substitution with  $\text{N}(\text{Me})_2$  this rule is less clear.

However, a more important result is found in the subseries of benzhydrylium ions (compounds **10–20** in Chart 1). For this series, the  $\sigma_p(\omega_C)$  values indicate that while for the double substitution with phenyl groups at  $\text{R}_2$  and  $\text{R}_3$  and some combination of *p*- $\text{CH}_3$  and *p*- $\text{OCH}_3$ , the global effect is activating ( $\sigma_p(\omega_C)>0$  for compounds **10–14** in Chart 1), some other combinations involving *p*- $\text{OCH}_3$ , *p*- $\text{N}(\text{Me})_2$ , (mfa)<sub>2</sub>, (mor)<sub>2</sub>, (thq)<sub>2</sub> and (pyr)<sub>2</sub>,<sup>9</sup> result in a global substituent effect that becomes deactivating ( $\sigma_p(\omega_C)<0$  for compounds **15–20** in Chart 1). Note that the highest activating effect is shown by the  $\text{Ph}_2\text{CH}^+$  ion ( $\sigma_p(\omega_C)=1.14$ , compound **10** in Chart 1), thereby suggesting that in this compound, two adjacent Ph groups cooperatively stabilize the carbocation by resonance. Increasing substitution by one and two methyl groups at *p*-position significantly attenuate this activation pattern (see compounds **11** and **12** in Chart 1). Other combination including mixed substitution with (Ph and *p*- $\text{OCH}_3$ ) and (*p*- $\text{OCH}_3$  and *p*- $\text{CH}_3$ ) result in a marginal electrophilic activation at the carbocation site (see for instance compounds **13** and **14** in Chart 1). Any combination of substitution involving *p*- $\text{OCH}_3$ , *p*- $\text{N}(\text{Me})_2$  and (mfa)<sub>2</sub>, (mor)<sub>2</sub>, (thq)<sub>2</sub> and (pyr)<sub>2</sub>,<sup>9</sup> on the other hand systematically result in increasing electrophilic deactivation at the carbocation site ( $\sigma_p(\omega_C)<0$ , for compounds **15** and **20** in Chart 1). Finally, for the subseries of substituted benzyl ions (compounds **21–28** in Chart 1) we may observe that for some combination of *p*- $\text{CH}_3$  or *p*- $\text{OCH}_3$  with  $\text{CH}_3$  and  $\text{OCH}_3$  groups at  $\text{R}_1$  and  $\text{R}_3$ , the global effect is activating ( $\sigma_p(\omega_C)>0$  for compounds **21–27** in Chart 1), with the only exception of compound **28**,

for which  $\sigma_p(\omega_C)<0$ . Note that the only difference with respect to compound **27** for which  $\sigma_p(\omega_C)>0$ , is the *p*- $\text{OCH}_3$  substitution at  $\text{R}_2$ . The effect observed in the cases of *p*- $\text{OCH}_3$  in compounds **24** and **28** may be again traced to resonance effects. For instance, while in compound **24** there is the possibility to form one oxonium structure at the *p*- $\text{OCH}_3$  position by resonance, structure **28** offers an additional oxonium resonant structure at  $\text{R}_3$ .

In summary, the reactivity pattern of the series of **28** carbenium ions considered in the present study may be rationalized in terms of a complex substituent constant  $\sigma_p(\omega_C)$  assessing the inductive effect for multiple substitution. This index is derived from the standard Hammett  $\sigma_p$  constant and the local electrophilicity index at the carbocation site for singly substitution using a four point equation. The  $\sigma_p(\omega_C)$  index not only assesses multiple inductive effects but some additional substituent effects like resonance seems to be incorporated in this new electronic descriptor of reactivity.

## 5. Concluding remarks

The local electrophilicity of a series of 28 carbenium ions has been ranked within an absolute theoretical scale. New substituent constants are introduced to account for the responses of the electrophilicity pattern induced by multiple substitutions at the carbocation site. The model correctly explains the experimental electrophilicity ordering established in terms of experimental scales.

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## References and notes

1. Ingold, C. K. *Recl. Trav. Chim.* **1929**, *48*, 797.
2. Swain, C. G.; Scott, C. B. *J. Am. Chem. Soc.* **1953**, *75*, 141.
3. Edwards, J. O. *J. Am. Chem. Soc.* **1954**, *76*, 1540.
4. Edwards, J. O.; Pearson, R. G. *J. Am. Chem. Soc.* **1962**, *84*, 16.
5. Mayr, H.; Patz, M. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 938.
6. Mayr, H.; Müller, K.-H.; Ofial, A. R.; Buhl, M. *J. Am. Chem. Soc.* **1999**, *121*, 2418.
7. Mayr, H.; Bug, T.; Gotta, M. F.; Hering, N.; Irrgang, B.; Janker, B.; Kempf, B.; Loos, R.; Ofial, A. R.; Remennikov, G.; Schimmel, H. *J. Am. Chem. Soc.* **2001**, *123*, 9500.
8. Mayr, H.; Kempf, B.; Ofial, A. R. *Acc. Chem. Res.* **2003**, *36*, 66.
9. Minegishi, S.; Mayr, H. *J. Am. Chem. Soc.* **2003**, *125*, 286.
10. Minegishi, S.; Kobayashi, S.; Mayr, H. *J. Am. Chem. Soc.* **2004**, *126*, 5174.

11. Maynard, A. T.; Huang, M.; Rice, W. G.; Covell, D. G. *Proc. Natl. Acad. Sci. U.S.A.* **1998**, *95*, 11578.
12. Parr, R. G.; Szentpály, L. v.; Liu, S. *J. Am. Chem. Soc.* **1999**, *121*, 1922.
13. Pérez, P.; Domingo, L. R.; Aurell, M. J.; Contreras, R. *Tetrahedron* **2003**, *59*, 3117.
14. Roy, R. K.; Krishnamurti, S.; Geerlings, P.; Pal, S. *J. Phys. Chem. A* **1998**, *102*, 3746.
15. Pérez, P.; Toro-Labbé, A.; Aizman, A.; Contreras, R. *J. Org. Chem.* **2002**, *67*, 4747.
16. Chattaraj, P. K.; Maiti, B.; Sarkar, U. *J. Phys. Chem. A* **2003**, *107*, 4973.
17. Contreras, R.; Andrés, J.; Safont, V. S.; Campodonico, P.; Santos, J. G. *J. Phys. Chem. A* **2003**, *107*, 5588.
18. Domingo, L. R.; Aurell, M. J.; Pérez, P.; Contreras, R. *J. Phys. Chem. A* **2003**, *106*, 6871.
19. Pérez, P. *J. Phys. Chem. A* **2003**, *107*, 522.
20. Pérez, P. *J. Org. Chem.* **2003**, *68*, 5886.
21. Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. J. A.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudín, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; W. Gill, P. M.; Johnson, B.; Chen, W.; Wong, M. W.; Andres, J. L.; Gonzalez, C.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. GAUSSIAN98, Revision A.6 Gaussian, Inc.: Pittsburgh, PA, 1998.
22. Parr, R. G.; Yang, W. *Density Functional Theory of Atoms and Molecules*; Oxford Science: Oxford, 1994.
23. Contreras, R.; Fuentealba, P.; Galván, M.; Pérez, P. *Chem. Phys. Lett.* **1999**, *304*, 405.
24. Fuentealba, P.; Pérez, P.; Contreras, R. *J. Chem. Phys.* **2000**, *113*, 2544.
25. Lucius, R.; Loos, R.; Mayr, H. *Angew. Chem., Int. Ed.* **2002**, *41*, 91.
26. Ritchie, C. D. *Can. J. Chem.* **1986**, *64*, 2239.