

Electronic Contributions to the σ_p Parameter of the Hammett Equation

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Received February 25, 2003

Abstract: A statistical procedure to obtain the intrinsic electronic contributions to the Hammett substituent constant σ_p is reported. The method is based on the comparison between the experimental σ_p values and the electronic electrophilicity index ω evaluated for a series of 42 functional groups commonly present in organic compounds.

One of the main goals in physical organic chemistry is the systematic description of the influence of chemical substitution in the reactivity pattern of molecules.¹ The major difficulty to achieve this objective is that substituent effects are experimentally assessed as global responses, and therefore steric and solvent effects may mask the intrinsic electronic contributions. Many detailed linear relationships between substituent groups and chemical properties have been developed to date.² In many cases, such relationships can be expressed quantitatively, thereby providing useful clues for interpreting reaction mechanisms and to predict reaction rates and equilibria.

The most widely applied of these relationships is the Hammett equation,³ which relates rates and equilibria of many reactions of compounds containing substituted phenyl groups, Ph-X. It is expressed by the following linear equation:

$$\log(k/k_0) = \sigma_p \rho \quad (1)$$

where k_0 is the rate (or equilibrium) constant for X = H, and k is the rate (or equilibrium) constant for the group X. The slope ρ is a constant for a given reaction under a given set of conditions, and σ_p is a constant characteristic of the group X. With the ρ value calculated for a given reaction at hand, and with known σ_p values for several

groups, the reaction rates for processes that have not been run can be predicted. The σ_p values embody the total electronic effects. These effects have their origin in four important contributions according to Topsom classification.⁴ They are (a) the substituent dipole leading to a field effect; (b) the electronegativity difference between the substituent and the atom directly attached to it, leading to an inductive or electronegativity effect; (c) charge transfer between suitable orbitals of the substituent and the group to which it is attached, leading to resonance or hyperconjugative effects; and (d) polarizability effects.⁴ This last contribution appears to be relatively small, except for large hydrocarbon substituents.⁴

A positive value of σ_p indicates an electron-withdrawing group, while a negative value is associated with an electron-releasing group. However, due to the fact that solvent effects may contribute to the σ_p parameter, it becomes very difficult to evaluate the intrinsic electronic contributions separately. The σ_p values are derived from experiments in solvents of high polarity, usually water or water/methanol mixtures,⁵ so they do not provide σ parameters containing only the intrinsic electronic contributions. These contributions are of interest for gas-phase reactions, or reactions that take place in solvents of very low polarity.

Theoretical models provide interesting alternatives to evaluate intrinsic electronic substituent effects. This can be done for instance by means of the response functions defined as global or local reactivity indices. The variations of a reactivity index for a set of functional groups attached to a common molecular frame may also be taken as a measure of the influence that the different substituents may have on the reactivity pattern of molecules. We have recently reported the use of the global electrophilicity index, ω , proposed by Parr et al.⁶ to classify a series of reagents present in Diels–Alder reactions,⁷ and in 1,3-dipolar cycloadditions.⁸ We found a good correlation between the difference in electrophilicity for the diene and dienophile or dipole and dipolarophile pair, $\Delta\omega$, and the feasibility of the cycloaddition. Substituent effects evaluated from $\Delta\omega$ on the diene/dienophile pair for related Diels–Alder reactions have also been found in good agreement with the experimental relative rates.⁹

The global electrophilicity index ω , which measures the stabilization in energy when the system acquires an additional electronic charge ΔN from the environment,

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has been given by the following simple expression:⁶

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

in terms of the electronic chemical potential μ and the chemical hardness η . Both quantities may be approached in terms of the one-electron energies of the frontier molecular orbital HOMO and LUMO, ϵ_H and ϵ_L , as $\mu \approx (\epsilon_H + \epsilon_L)/2$ and $\eta \approx \epsilon_L - \epsilon_H$, respectively.¹⁰ The electrophilicity index encompasses both, the propensity of the electrophile to acquire an additional electronic charge (driven by μ^2 , the square of electronegativity) and the resistance of the system to exchange electronic charge with the environment described by η , simultaneously. A good electrophile is in this sense characterized by a high value of μ and a low value of η . Note that in the present approach, the environment may be represented by either external effects, coming for instance from the interaction with the solvent, or the intrinsic electronic effects coming from the presence of substituent groups in the isolated molecule.

In this Note, we show that the intrinsic electronic contribution to the Hammett substituent constant, $\sigma_e(\omega)$, may be obtained from a statistical analysis that follows from the comparison of the experimental σ_p values and the electronic electrophilicity index ω evaluated for isolated molecules. The analysis was performed for the electrophilicity power of a series of substituted ethylenes, $X-CH=CH_2$, and the σ_p values reported by Hansch et al.⁵ for a wide list of functional groups (FG), $X-$, commonly present in organic compounds. The choice of this reduced model system is based on previous results reported by Katritzky et al.,¹¹ who found that the conjugative interaction between substituents and an adjacent C=C bond seems to parallel that between substituents and benzene rings. Substituent effects also have been discussed recently for ketenimines, isocyanides, and nitriles.¹²

For this study, we selected 42 representative FGs from a list of more than 500 substituents compiled by Hansch et al.⁵ The ω values for the corresponding ethylene derivatives were calculated at the B3LYP/6-31G* level of theory, using the Gaussian98 suite of programs.¹³ The electrophilicity index ω for the whole series of ethylene

TABLE 1. Electrophilicity, ω (in eV), for the Substituted Ethylenes $X-CH=CH_2$, Hammett Constants, σ_p , for the Substituents X, and Computed $\sigma_e(\omega)$ ^a

| | | ω | σ_p | $\sigma_e(\omega)$ |
|------------|----------------------------------|----------|------------|--------------------|
| 1 | SMe ₂ ⁺ | 6.01 | 0.90 | 1.31 |
| 2 | PMe ₃ ⁺ | 5.43 | 0.73 | 1.25 |
| 3 | NMe ₃ ⁺ | 5.00 | 0.82 | 1.20 |
| 4* | NO | 3.30 | 0.91 | 0.94 |
| 5* | NO ₂ | 2.61 | 0.78 | 0.79 |
| 6* | COCF ₃ | 2.45 | 0.80 | 0.76 |
| 7 | CBr ₃ | 1.98 | 0.29 | 0.62 |
| 8 | COPh | 1.96 | 0.43 | 0.62 |
| 9 | CHO | 1.83 | 0.42 | 0.57 |
| 10 | CN | 1.74 | 0.66 | 0.54 |
| 11* | COMe | 1.65 | 0.50 | 0.51 |
| 12 | C ₆ F ₅ | 1.62 | 0.27 | 0.50 |
| 13* | CO ₂ H | 1.61 | 0.45 | 0.50 |
| 14* | COCHMe ₂ | 1.60 | 0.47 | 0.48 |
| 15* | COEt | 1.57 | 0.48 | 0.48 |
| 16* | CCl ₃ | 1.57 | 0.46 | 0.48 |
| 17* | CO ₂ Me | 1.51 | 0.45 | 0.46 |
| 18* | NC | 1.48 | 0.49 | 0.44 |
| 19* | CO ₂ Et | 1.48 | 0.45 | 0.44 |
| 20 | SiH ₃ | 1.33 | 0.10 | 0.38 |
| 21* | CONH ₂ | 1.32 | 0.36 | 0.37 |
| 22 | CF ₃ | 1.31 | 0.54 | 0.37 |
| 23 | N ₃ | 1.30 | 0.08 | 0.36 |
| 24 | C(CF ₃) ₃ | 1.26 | 0.55 | 0.34 |
| 25* | CONHMe | 1.20 | 0.36 | 0.31 |
| 26 | Ph | 1.13 | -0.01 | 0.28 |
| 27 | OCOMe | 1.01 | 0.31 | 0.21 |
| 28 | Cl | 0.91 | 0.23 | 0.14 |
| 29 | SMe | 0.90 | 0.00 | 0.13 |
| 30 | Br | 0.89 | 0.23 | 0.13 |
| 31 | SiMe ₃ | 0.83 | -0.07 | 0.08 |
| 32* | H | 0.73 | 0.00 | 0.00 |
| 33 | F | 0.68 | 0.06 | -0.04 |
| 34 | SH | 0.65 | 0.15 | -0.07 |
| 35* | Me | 0.60 | -0.17 | -0.12 |
| 36* | Et | 0.58 | -0.15 | -0.14 |
| 37* | Pr | 0.58 | -0.13 | -0.14 |
| 38* | OSiMe ₃ | 0.45 | -0.27 | -0.30 |
| 39* | OH | 0.44 | -0.37 | -0.31 |
| 40* | OMe | 0.42 | -0.27 | -0.34 |
| 41 | NH ₂ | 0.30 | -0.66 | -0.55 |
| 42 | NMe ₂ | 0.27 | -0.82 | -0.61 |

^a Selected data for regression in Figure 2 are indicated with an asterisk.

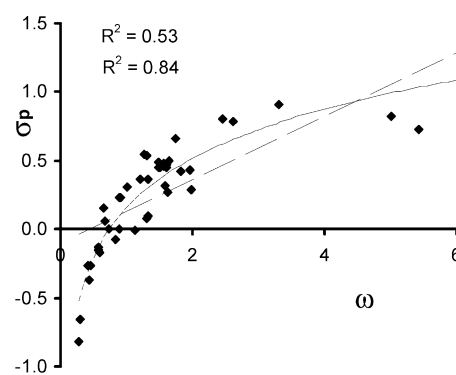


FIGURE 1. Plot of σ_p vs the electrophilicity ω for the substituted alkene series.

derivatives, together with the experimental σ_p given by Hansch et al.⁵ are listed in Table 1.

The procedure to obtain estimates of the intrinsic electronic substituent effects from the reactivity index ω was as follows: we first compared the computed ω values with the experimental σ_p (see Figure 1). The analysis revealed a poor linear correlation between both quantities, with a regression coefficient of $R_2 = 0.53$. A

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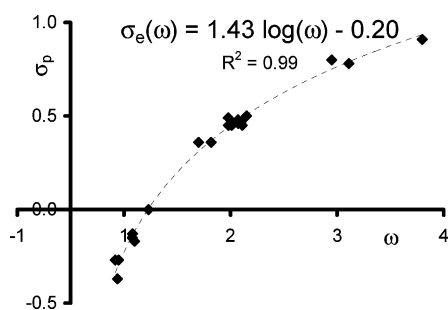


FIGURE 2. Plot of σ_p vs the electrophilicity ω for the selected subseries of substituted alkenes.

better correlation was found when all 42 points were fitted to a logarithm curve ($R_2 = 0.84$, see Figure 1). The poor linear correlation observed for the whole series of molecules can be attributed in part to bulk and solvent effects encompassed in the experimental σ_p values. Thus, when the data for 20 selected FGs of the series marked with an asterisk in Table 1 were analyzed, the logarithmic correlation was significantly improved ($R_2 = 0.99$ see Figure 2).

This analysis allows us to find a valuable logarithmic correlation between the experimental Hammett substituent parameter σ_p and the electrophilicity index given by:

$$\sigma_e(\omega) = 1.43 \log(\omega) - 0.20 \quad (3)$$

where $\sigma_e(\omega)$ represents the theoretical electronic contribution to the experimental Hammett substituent constant σ_p values and ω is the electrophilicity index for the corresponding substituted ethylene. Note that this subseries contains FGs classified from strong electron-withdrawing, NO_2 , to strong electron-releasing, OCH_3 .

Values of the computed $\sigma_e(\omega)$ for the whole series of 42 compounds are compared with the σ_p values in the last two columns of Table 1. An analysis of σ_p versus $\sigma_e(\omega)$ values for the whole series given in Table 1 is displayed in Figure 3 ($R_2 = 0.84$). Deviation of the proposed $\sigma_e(\omega)$ values from the experimental σ_p ones can be mainly traced to the presence of bulk and solvent effects encompassed in the σ_p Hammett parameter.

The consistency of the theoretical $\sigma_e(\omega)$ scale may be illustrated as follows: the series SMe_2^+ , PMe_3^+ , and NMe_3^+ , which have the largest $\sigma_e(\omega)$ values, 1.31, 1.25, and 1.20, corresponds to the most electron-withdrawing FGs within the series. These values are larger than the experimental σ_p values: 0.90, 0.73, and 0.82, respectively. This significant deviation of $\sigma_e(\omega)$ from the experimental σ_p values can be traced to large solvent effects due to the positive charge present in these groups.

CCl_3 and COEt , which have mainly inductive and resonance effects, respectively, display similar $\sigma_e(\omega)$ values, ≈ 0.48 , in agreement with the similar σ_p values found experimentally (0.48 and 0.46, respectively).

The $\sigma_e(\omega)$ values predicted for the CHO and COMe, 0.57 and 0.51, are consistent with the larger electrophilic character expected for aldehydes with respect to ketones. Note, however, that the $\sigma_p = 0.42$ quoted for the CHO in

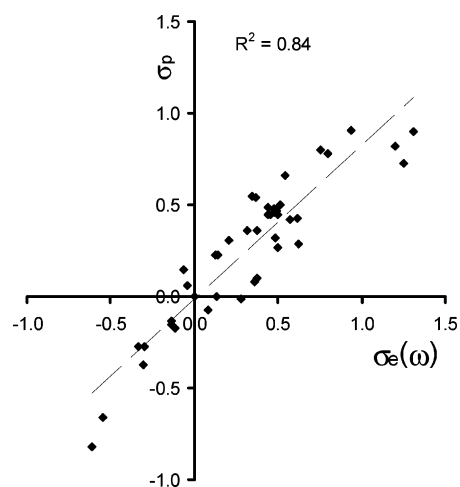


FIGURE 3. Plot of σ_p vs computed $\sigma_e(\omega)$ for the complete series of substituted alkenes.

Hansch's scale⁵ is lower than that measured for the COMe one ($\sigma_p = 0.50$).

For the carbonyl, COR, and carboxyl, COX, subseries there is good correlation between the σ_p and $\sigma_e(\omega)$ values, which are also consistent with the electrophilicity pattern predicted for the corresponding ethylene derivatives. The electron-withdrawing substitution at the carbonyl group increase both σ_p and $\sigma_e(\omega)$. Note that for the FGs located in the middle of the series displayed in Table 1, the σ_p and $\sigma_e(\omega)$ have approximately the same values.

The electron-releasing groups located at the end of Table 1 present also a good correlation with the σ_p values. The $\sigma_e(\omega)$ values predicted for the OH and OMe, -0.31 and -0.34 , are consistent with the larger nucleophilic character expected for the methoxy group with respect to the hydroxyl one. Note, however, that the $\sigma_p = -0.27$ quoted for OMe in Hansch's scale⁵ is lower than that measured for OH ($\sigma_p = -0.37$).

In summary, the calculated electrophilicity index, ω , for a series of substituted ethylenes may be used to make reliable estimates of the intrinsic electronic contributions to the σ_p constants of the Hammett equation, for a series including 42 functional groups commonly present in organic compounds. The computed $\sigma_e(\omega)$ parameters account for the intrinsic electronic substituent effects that are contained in the experimental values of the σ_p substituent constants. This $\sigma_e(\omega)$ scale is expected to be a useful predictive tool to assess the reactivity pattern of gas-phase reactions or those reactions that take place in solvents of very low polarity.

Acknowledgment. This work received partial financial support from the Ministerio de Educación y Cultura of the Spanish Government by DGICYT (project BQU2002-01032), and Fondecyt, grant Nos. 1020069 and 1030548. L.R.D. thanks the Fondecyt grant No. 7020069 for financial support and the Universidad Andrés Bello and the Universidad de Chile for their warm hospitality.

JO030072J