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Intrinsic reactivity index as a single scale directed toward both electrophilicity and nucleophilicity using frontier molecular orbitals

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ABSTRACT

A theoretical intrinsic reactivity index (IRI) is introduced through analysis of the ω, ε correlation (*Tetrahedron Lett.* **2013**, *54*, 339–342). The index is valid as a single scale directed toward both electrophilicity and nucleophilicity using the energy levels of frontier molecular orbitals. Linear correlations of IRI values with various chemical properties are available for a wide range of reactivity. A striking example of a fair linear correlation of IRI values of benzhydryl cations with Mayr's electrophilicity parameter E is described.

1. Introduction

In all chemical reactions, involving biological reactions, interactions between electrophiles and nucleophiles are intensively addressed at the initial stage of the reaction, irrespective of ionic or radical processes. To understand the behavior of molecules of interest in such reactions, it is preferable to use reliable theoretical reactivity indices, ones in which the concepts of electrophilicity and nucleophilicity of molecules are important to most chemists. Although numerous methods have been developed for determining electrophilicity and nucleophilicity, and consequently improving our understanding of molecular behavior,[1–9] as far as we know, no single theoretical scale valid for both these concepts has been proposed so far. Thus, we aim to propose an effective scale over the wide range of reactivity of chemical species.

In Fukui's frontier molecular orbital theory[10,11] nucleophilicity is related to the energy level of the highest occupied molecular orbital (HOMO), while electrophilicity is characterized by that of the lowest unoccupied molecular orbital (LUMO). According to Koopmans' theorem,[12] the energy of HOMO is approximately equal to the negative of ionization potential and that of LUMO is identified as the negative of electron affinity. One should keep in mind, however, that electron relaxation and correlation effects tend to substantially and fortuitously cancel out. Fukui's conventional treatment might provide a valid method of constructing useful indices of chemical reactivity based on frontier molecular orbitals.

Electronegativity (χ)[13] and hardness (η)[14] are two fundamental indices of chemical reactivity. In the density-functional theory (DFT),[15] electronegativity (χ)[16] and hardness (η)[17] are quantitatively defined for an N-electron system with total energy E, as follows.

$$\chi = -\mu = -\left(\frac{\partial E}{\partial N}\right)_{\nu} \quad \eta = \frac{1}{2}\left(\frac{\partial^2 E}{\partial N^2}\right)_{\nu} \tag{1}$$

Parr et al. based their consideration of electrophilicity on DFT.[18–20] Accordingly, energy change depends on electron transfer in charge-transfer models. This transfer is presented by a second-order Taylor series expansion of energy as a function of number of electrons, N, the energy change is described by

$$(f(N) =)E = \mu N + \frac{\eta}{2}N^2 \tag{2}$$

where μ is the electronic chemical potential (negative of electronegativity) and η is chemical hardness, as mentioned above.[21] Parr's introduction of μ and η as the coefficients showed to be an ordinary quadratic equation. Setting $f'(N)=0$ gives $N=-\mu/\eta$, substituting $-\mu/\eta$ for N into the Eq. 2 yields the minimum value of total energy, $E=-\mu^2/2\eta$, as shown in Fig. 1. Parr proposed the ω index as the measure of electrophilicity, which is directly related to the energy difference corresponding to the change in electronic charge in the system undergoing the charge transfer process. Parr found a correlation between the index and electron affinity of atoms and molecules.[19]

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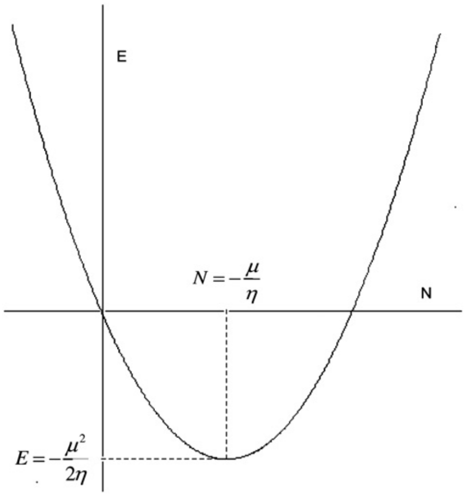

Fig. 1. Parabola with Eq. 2.

$$\omega = \frac{\mu^2}{2\eta} \tag{3}$$

To realize a simple theoretical scale, we focused on the introduction of the ω index for electrophilicity. Analyzing the extremum of the graph, we recognized that ω is not an independent variable and $-\mu^2/2\eta$ $(=-\omega)$ is a function of $-\mu/\eta$ in the second-order parabola. The ω value must be accompanied by the corresponding value related to $-\mu/\eta$. When μ/η is expressed as ε, the relation between ω and ε is given by a parabola, as shown below (Fig. 2).

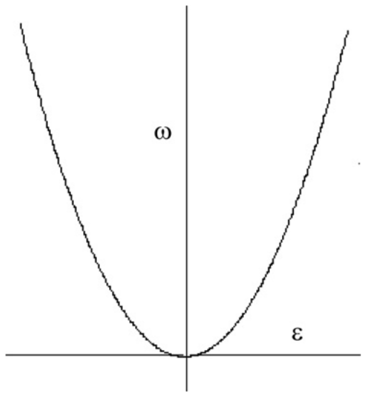

Fig. 2. Parabola with Eq. 4.

$$\omega = \frac{\eta}{2}\varepsilon^2 \tag{4}$$

Eq. 4 gives a complete parabola only if hardness is constant but when the hardness values are within an appropriate range, they allow the formation of a parabola.

The validity of this concept was examined with 65 chemical species using Koopmans' approximation at the HF/6-31G(d,p) level of theory and the ω, ε treatment where the ω values plotted against the ε values expectedly gave a fine parabola, as shown in Fig. 3.[22]

$$\mu \approx \frac{E_{\mathrm{LUMO}} + E_{\mathrm{HOMO}}}{2} \qquad \eta = E_{\mathrm{LUMO}} - E_{\mathrm{HOMO}} \tag{5}$$

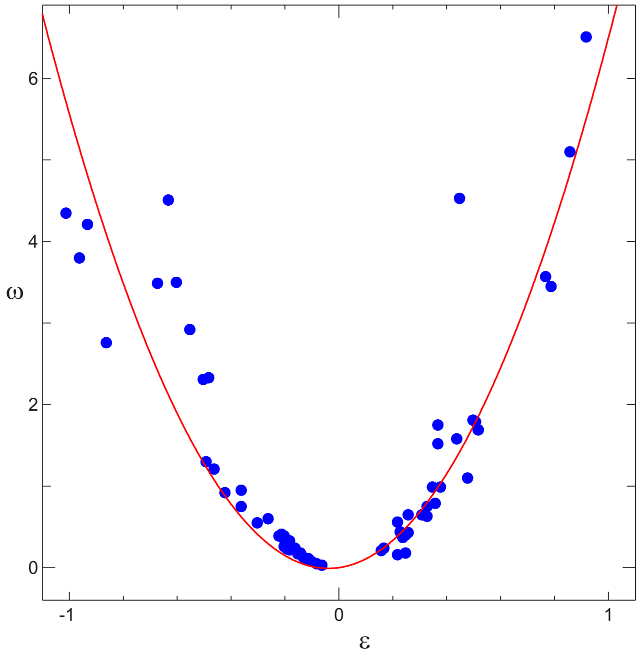

Fig. 3. ω, ε Correlation of 65 chemical species, computed at the HF/6-31G(d,p) level of theory.[22]

Regression analysis of the ω, ε correlation produced a parabola (ω=6.03ε^2, R=0.885), which is unambiguously attributable to the original equation via the definition of the ω and ε. The coefficient of ε^2 should be comparable with $\eta/2$ in Eq. 4 and the value of 6.03 is quite consistent with 7.60, calculated from the average η of the 65 compounds. As depicted in this graph, the ω index effectively portrays the continuous behavior of chemical reactivity as a single scale from high electrophilicity to high nucleophilicity along the ε values. A similar approach has so far developed within the context of conceptual DFT.[5] Chattaraj et al.[23] have suggested a multiplicative inverse of the electrophilicity index ($1/\omega$) as well as an additive inverse ($-\omega$) under the assumption that electrophilicity and nucleophilicity are inversely related.[24] However, although the above treatment of ω and ε is acceptable, we propose a more precise and practical intrinsic reactivity index (IRI), derived simply from the ε values, as a single scale for chemical reactivity. We discuss this proposal in detail in this paper.

2. Computational details

All equilibrium structures were fully optimized with C_1 symmetry and were analyzed by frequency computations at the MP2/6-31G(d,p)//MP2/6-31G(d,p) and MP2/6-31+G(d,p)//MP2/6-31+G(d,p) levels of theory. More detailed conformations were analyzed at the B3LYP level using the 6-31G(d,p) basis set. The η, μ, ω, ε, and IRI values were obtained using the HOMO and LUMO energy levels calculated at the MP2/6-31G(d,p) and MP2/6-31+G(d,p) levels. These quantum chemical calculations were performed using the Gamess program and the Gaussian 09 program package. (See Supplementary data for full details.)

3. Results and discussion

3.1. Intrinsic reactivity index as a single scale

Note that ω is recognized as the index accompanying ε. It is not adequate for representing the linear correlations commonly exhibited by a variety of chemical properties because it is the square of μ, and hence, the plot is a parabola. Here, we point out that ε is dimensionless, while ω value is a measure of energy.