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On the intrinsic reactivity index for electrophilicity/nucleophilicity responses

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Abstract We present a critical discussion related to the recent definition of the *intrinsic reactivity index*, IRI, (Tetrahedron Lett. 2013, 54, 339-342; Tetrahedron 2013, 69, 4247-4258) formulated to describe both, electrophilicity (charge acceptance) and nucleophilicity (charge donation) reactivities. We here stress that such an IRI model, based on the quantity μ/η, should be properly related to theoretical approximations associated to the change in the global electronic energy of a given chemical system under interaction with a suitable electron bath (Gazquez JL et al. J Phys Chem A 2007, 111, 1966-1970). Further, the limitations of the IRI model are presented by emphasizing that the intrinsic relative scales of electrophilicity and nucleophilicity within a second-order perturbation approach must account for the further stabilization of the two interacting species (Chamorro E et al. J Phys Chem A 2013, 117, 2636-2643).

Keywords Charge transfer · Chemical hardness · Chemical potential · Electrophilicity · Nucleophilicity · Reactivity scales

Introduction

Recently, Kiyooka and co-workers [1, 2] have identified the relation between the chemical potential μ and the molecular

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hardness η [3–6] as the basis for the definition of an intrinsic reactivity index (IRI). They claimed that IRI, defined as $IRI \equiv 2\varepsilon$, where, $\varepsilon \equiv \mu/\eta$, provides a single scale to classified both, electrophilic and nucleophilic reactivity of chemical species. Using the simplest approach for the evaluation of chemical potential and hardness in terms of molecular orbitals, namely $\mu \approx (E_{HOMO}-E_{LUMO})/2$ and $\eta \approx (E_{LUMO}-E_{HOMO})$, the authors found a parabola fitting between Parr's electrophilicity index $\omega \equiv \mu^2/2\eta$ [7–10], and the proposed ε when several molecular systems were examined. These systems ranking from strong nucleophiles to strong electrophiles become categorized according to the sign of the ε parameter, that is, positive ε values for the former and negative ε values for the later. In the present work we focus on these interesting results in order to stress some points that deserve, as will be noted, further conceptual consideration and discussion.

Results and discussion

Starting with the second order Taylor expansion of the energy as a function of the electron transfer at fixed external potential, $v(r)$, i.e., $\Delta E = \mu \Delta N + \frac{1}{2}\eta \Delta N^2$, we first notice that the quantity ε is not dimensionless, as it was erroneously stated [1, 2]. This follows directly from the definition of the global indices $\mu \equiv [\partial E/\partial N]_{v(r)}$ and $\eta \equiv [\partial^2 E/\partial N^2]_{v(r)}$. Thus, the ε parameter simply stands for $\varepsilon \equiv [\partial E/\partial \mu]_{v(r)}$, and represents indeed a number of electrons [11]. Based on the original derivation of the electrophilicity index [7–10], the quantity ε corresponds to the negative of the maximum amount of electronic charge ΔN transferred toward an electrophile immersed in an electron sea (i.e., an electron bath with chemical potential and molecular hardness equal to zero). Due to this maximum charge transfer the electrophile will become energetically stabilized by an amount equal to $-\omega$ [7].

It should also be pointed out, as explicitly stated by Gázquez, Cedillo, and Vela (GCV) [12], that the chemical responses (both global and local) of a given system to charge donation or charge acceptance are intrinsically different. Therefore, by considering a chemical system immersed in an environment that may either accept or donate electronic charge, GCV have successfully defined the so called electrodonating and electroaccepting power [12], i.e., $\omega^{\mp} \equiv (\mu^{\mp})^2 / 2\eta^{\mp}$. Here, the minus superscript is associated to the intrinsic response of the system when transferring charge to the electron bath, and the plus superscript is related to the system's response when withdrawing charge from the surrounding bath. The original derivation of ω can be recovered by assuming that $\mu^{\mp}$ and $\eta^{\mp}$ indexes are simply μ and η, making no distinction between the reactive proclivities to charge acceptance/donation processes [7, 12]. Within this context, the proposed IRI scale [1, 2] would have limited applicability to nucleophilic reactivity.

Following GCV [7, 12], when a chemical system is surrounded by an electron bath with chemical potential μ_{bath}, the changes in its grand potential are $\Delta\Omega^{\mp} \equiv \Delta E^{\mp} - \mu_{bath}\Delta N^{\mp}$. The constrained minimization of this grand potential with respect to $\Delta N^{\mp}$ yields the optimum amount of charge transferred, $(\Delta N^{\mp})^* = -(\mu^{\mp} - \mu_{bath})/\eta^{\mp}$ [13, 14]. Since the molecular hardness $\eta^{\mp}$ is always positive [15–19] the direction of charge flow will be naturally driven by the chemical potential of the bath. Specifically, in the case of $\mu^- > \mu_{bath}$ we have $(\Delta N^-)^* < 0$ and the system is donating charge to the environment, whereas if $\mu^+ < \mu_{bath}$ we get $(\Delta N^+)^* > 0$ and the system is accepting charge from the environment.

Now, let us evaluate the change in the electronic energy of the system when the optimal amount of charge, $(\Delta N^{\mp})^*$, has been transferred, $\Delta E^{\mp}((\Delta N^{\mp})^{\rightarrow}) = -\frac{1}{2\eta^{\mp}}\left[(\mu^{\mp})^2 - (\mu_{bath})^2\right]$. Thus, within the validity of the imposed constraints, whether or not the chemical system is gaining stability in the electron transfer process, will explicitly depend upon the difference between the chemical potential of the system and the bath, $(\mu^{\mp})^2 - (\mu_{bath})^2$.

In this context, it is important to understand that the IRI scale recently proposed by Kiyooka and co-workers [1, 2] is intrinsically referring (and therefore limited) to chemical responses of a given system immersed in an electron bath with $\mu_{bath} = 0$. Under such considerations and within the context of the simplest approximations to the global reactivity responses (i.e., finite differences and frontier molecular orbital energies), any system with *negative* chemical potential values correspond to electrophiles while only chemical systems with *positive* chemical potential (and only those systems) can be categorized as nucleophiles because they will indeed become more stable when undergoing charge donation, $\Delta E^- < 0$! Thus, owing these constrains the IRI scale would have limited applicability to predict nucleophilicity. For instance, the model fails when trying to determine electrophilic and nucleophilic reactivity of singlet carbenes, as evidenced by Moss and co-workers [20].

Finally, we would like to emphasize that within the current framework of rationalizing electronic aspects of electrophilicity and nucleophilicity responses [21–25], the correct choice of the chemical potential value for the electronic bath would further widen the scope of applicability. As has been recently shown [26], the explicit incorporation of the chemical potential (and hardness) of the reactive partner to simulate the surrounding environment of a given chemical species, provides a useful way to properly categorize the relative electrophilicity/nucleophilicity responses when building theoretical electronic analogues of the well-known experimental scales of Mayr and coworkers [27–30].

Conclusions

The analysis presented above clearly shows that, for general applications, the definition of a suitable chemical potential for the surrounding bath becomes the key consideration to establish a general reactivity scale. We certainly hope that the ideas discussed here will contribute to further advance the theoretical schemes [13, 14, 31, 32] that aim to explain the experimental electrophilicity and (particularly) nucleophilicity reactivity scales [27–30, 33].

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