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Calculations show that the regioselectivity of free radical addition to olefins can be rationalized by using local reactivity indices derived from density functional theory, such as the condensed Fukui functions and atomic softness.

Introduction

The hard and soft acids and bases (HSAB) principle has long played a useful role in explaining the behaviour of many chemical systems.¹⁻³ This concept gains impetus with the observation that density functional theory (DFT) provides a necessary and efficient framework for a quantitative description of many global and local parameters (including hardness and softness) directly related to the inherent reactivity of chemical species.⁴ The HSAB principle has also been invoked in a local sense to explain the response of a chemical system to different kinds of reagents.⁵⁻⁹ In particular, Fukui functions¹⁰ and local softness¹¹ may be used to determine the nature of reactive sites of a given molecule. Generally it is believed that the larger the value of the Fukui function the greater the reactivity. However, current understanding has been changing with the recent proposal of Gazquez and Méndez.¹² They propose that when two molecules A and B interact, then a bond is likely to form between an atom of A and an atom of B whose Fukui function values are similar. They also propose that local softness may play the same role as the Fukui function when the softness of the two interacting molecules is different. This can be taken as a local version of the HSAB principle.¹ The proposition was subsequently verified by Geerlings and co-workers.¹³ The determination of the specific sites of interaction between two chemical species is of fundamental importance in determining the products of a given reaction without actual calculations of the corresponding potential energy surface.

Free radical addition to olefins is an area of continuing research interest.¹⁴⁻²⁰ There have been many attempts¹⁶⁻¹⁹ to rationalize theoretically the mechanism of addition using the results obtained from conventional molecular orbital calculations. Now with the recent development of various local reactivity indices, such as the condensed Fukui function, local softness *etc.*, we feel it is worth revisiting the problem of free radical addition to olefins from a different viewpoint. The main objective of the present paper is to observe whether DFT based reactivity descriptors such as condensed Fukui function and local softness parameters can be used to predict the preferred site of free radical attack upon olefins. To this end, variation of Fukui function and atomic softness with different substituents on the olefins are considered. To our knowledge, this is the first attempt to apply DFT based reactivity descriptors to the study of free radical addition to olefins.

Method

The Fukui function $f(r)$ is defined¹⁰ as the first derivative of the electronic density $\rho(r)$ with respect to the number of electrons N at constant external potential $v(r)$. Thus:

$$f(r) = [\partial\rho(r)/\partial N]_{v(r)} = [\delta\mu/\delta v(r)]_N \quad (1)$$

The second equality follows from the Maxwell relation.²¹ Local softness¹¹ $s(r)$ is defined as the derivative of the electronic density with respect to the chemical potential at constant $v(r)$.

$$s(r) = [\partial\rho(r)/\partial\mu]_{v(r)} \quad (2)$$

From eqns. (1) and (2), $s(r)$ can be written as:

$$s(r) = [\partial\rho(r)/\partial N]_v [\partial N/\partial\mu]_v = Sf(r) \quad (3)$$

where $S = (\partial N/\partial\mu)_v$ is the global softness.¹¹ Because $f(r)$ and $s(r)$ allow one part of a molecule to be distinguished from another, we should be able to use them to differentiate the reactive behaviour of different atoms in a molecule. Yang and Mortier⁵ later defined $f(r)$ in a more condensed form. The condensed Fukui functions⁵ of an atom, say k , in a molecule with N electrons are defined as:

$$f_k^+ = [q_k(N+1) - q_k(N)] \quad \text{for nucleophilic attack,}$$

$$f_k^- = [q_k(N) - q_k(N-1)] \quad \text{for electrophilic attack and}$$

$$f_k^0 = [q_k(N+1) - q_k(N-1)]/2 \quad \text{for radical attack,}$$

where q_k is the electronic population of atom k in a molecule. Using eqn. (3) the corresponding local softness parameters can be defined as:

$$s_k^i = f_k^i S, \text{ where } i = +, - \text{ or } 0$$

In density functional theory, hardness (η) is defined as:⁴

$$2\eta = (\partial^2 E/\partial N^2)_{v(r)} = 1/S$$

In the finite difference approximation, S can be approximated as:²

$$S = 1/(E_i - E_{ea})$$

where E_i and E_{ea} are the first vertical ionization energy and electron affinity of the molecule respectively.

In the present study all calculations were carried out through density functional procedures using B3LYP^{22,23} exchange correlation functional and 6-31G(d,p) basis functions except for the four olefins containing a phenyl group, for which a 3-21G basis set was used. The energies and gross atomic charges (q) for the $N+1$ and $N-1$ electron systems were calculated at the optimized geometry of the N -electron system due to the constraint of constant external potential in the definition of Fukui functions. The electronic population of various atoms in the N , $N+1$ and $N-1$ electron systems were calculated following the

Table 1 The condensed Fukui functions for radical attack and atomic softnesses of the two carbon atoms of the substituted olefins calculated by using the B3LYP/6-31G(d,p) method. The last two rows present the values of the same parameters for the two radicals.

Molecule	S	Atom ^a	f^0	s^0	SD ^b	SD ^c
H ₂ C=CHF	2.00	C ¹	0.528	1.056	1.537	1.267
		C ²	0.215	0.429	2.164	1.894
H ₂ C=CHCl	2.19	C ¹	0.537	1.175	1.418	1.148
		C ²	0.050	0.109	2.484	2.214
H ₂ C=CHCH ₃	2.11	C ¹	0.545	1.148	1.445	1.175
		C ²	0.212	0.446	2.147	1.877
H ₂ C=CHCF ₃	2.08	C ¹	0.510	1.061	1.532	1.262
		C ²	0.257	0.534	2.059	1.789
H ₂ C=CHNH ₂	2.23	C ¹	0.524	1.169	1.425	1.155
		C ²	0.049	0.108	2.485	2.215
H ₂ C=CHOH	2.11	C ¹	0.531	1.120	1.473	1.203
		C ²	0.198	0.419	2.174	1.905
H ₂ C=CHSiH ₃	2.25	C ¹	0.446	1.004	1.589	1.319
		C ²	0.222	0.498	2.095	1.825
H ₂ C=CHCN	2.36	C ¹	0.369	0.873	1.720	1.450
		C ²	0.213	0.504	2.089	1.819
H ₂ C=CHNO ₂	2.48	C ¹	0.258	0.639	1.954	1.684
		C ²	-0.020	-0.050	2.643	2.373
H ₂ C=CHCHO	2.59	C ¹	0.286	0.740	1.853	1.583
		C ²	0.019	0.050	2.543	2.273
HFC=CF ₂	1.99	C ¹	0.413	0.823	1.770	1.500
		C ²	0.213	0.424	2.169	1.899
HFC=CHCl	2.20	C ¹	0.353	0.776	1.817	1.547
		C ²	0.151	0.332	2.261	1.991
CH ₃	2.30	C	1.130	2.593		
CF ₃	2.27	C	1.024	2.323		

^a C¹ represents the carbon atom at the less substituted end. ^b Difference in softness values between the carbon atom in CH₃ and the doubly bonded carbon atoms in the olefins. ^c Difference in softness values between the carbon atom in CF₃ and the doubly bonded carbon atoms in the olefins.

method of electrostatic potential (ESP) derived charges and using the option MK in the Gaussian-94 program package.²⁴ It is now well known^{25,26} that ESP derived charges are a better descriptor of the electron density distribution in a molecule and have a less weak basis set dependence than the Mulliken charges.

Results and discussion

We considered the addition of two radicals CH₃ and CF₃ to a series of olefins H₂C=CHX (X = F, Cl, NH₂, CH₃, CF₃, SiH₃, OH, NO₂, CN, CHO), F₂C=CHF and HFC=CHCl. It has been shown¹⁹ from the ionization energies and electron affinities of the olefins and methyl radicals that for X = F, H, OH, CH₃, SiH₃ and NH₂, the methyl radical behaves as an electron acceptor, whereas for X = CHO, NO₂ and CN it acts as a weak donor. We observed this same trend from our DFT calculations showing that the methyl radical does not display any general nucleophilic behaviour. However, in the present context we did not need to consider its general behaviour but used the condensed Fukui function for radical attack f^0 and local softness s^0 to determine the regioselectivity of the radical attack upon different olefins. Generally, the attack occurs at the less substituted end of the olefin.^{15,16,19} However, there are a few exceptions, for example, in the case of F₂C=CHF, the methyl radical preferentially attacks the more substituted end (CF₂) whereas CF₃ attacks the less substituted end (CHF).

Table 1 presents the condensed Fukui function and the softness of radical attack at both the doubly bonded carbon atoms in the different olefins. The softness differences between the carbon atom in CH₃ (or CF₃) and the two double bonded carbon atoms of the olefins are also presented. The atom with a larger s^0 value is softer. Considering the proposal of Gazquez and Méndez¹² it is expected that radical attack will be at the

olefin atom with a softness value closer in magnitude to that of the carbon atom of the radical. On the other hand, one would also expect that free radical attack will preferentially be on an atom which has the larger value of Fukui function for radical attack. In the present context both the above mentioned factors act in the same direction. It is obvious from Table 1 that the carbon atom at the less substituted end (C¹) has a larger f^0 or s^0 value than that of the carbon atom at the more substituted end (C²). In the case of HFC=CHCl, the carbon atom attached to the fluorine (C¹) has a larger s^0 value than that of the carbon atom attached to the chlorine (C²). Hence C¹ atom is softer or more susceptible to radical attack than C². It is thus expected that the radical attack will preferentially be at the C¹ carbon atom. As the s^0 values of the carbon atoms of the two radicals are always larger than those of the two doubly bonded carbon atoms of the olefins, s^0 values of C¹ carbon atoms, which are always larger than s^0 values of the C² atoms, are uniformly closer to those of the radical. Thus there is a propensity for a novel bond to be formed between the radical and the C¹ carbon atom. In the case of F₂C=CHF, the present calculation shows that the carbon atom attached to one fluorine atom (C¹) has greater softness than the other carbon atom and thus both CH₃ and CF₃ radicals should preferentially attack on the C¹ carbon atom. But experimentally it has been observed¹⁵ that the CH₃ radical instead adds preferentially to the carbon atom bonded to two fluorine atoms, although the CF₃ radical prefers the carbon atom bonded to a single fluorine atom as predicted. This only case of failure of the present approach in the case of CH₃ addition to HFC=CF₂ may be due to the strong electronic reorganization inside the supermolecule which is not accounted for in the separated molecule approach taken here.

One might expect a correlation between the atomic softness value of the olefins and the transition state barrier for a particular type of radical. It has been shown¹⁹ by very high level *ab initio* calculations [QCISD(T)/6-311G**] that the barrier height for methyl radical attack on CH₂=CHX decreases in the order X = F > OH > CH₃ > NH₂ > SiH₃ > Cl > CHO > NO₂ > CN. Now if we look at the s^0 values of the C¹ carbon atom of the olefins, we find that there is no general correlation between the s^0 value and the barrier height. However, if we differentiate the three π -electron accepting groups (CHO, NO₂ and CN) from the other substituents (X), we do find a correlation between the s^0 values of the C¹ atoms of olefins and the barrier heights for methyl attack, except where X = SiH₃. The barrier height decreases with the increase in s^0 value. The reason why the barrier heights are substantially lower for the three π -electron accepting substituents (CHO, NO₂ and CN) cannot be explained by the s^0 values alone. It has already been pointed out by Wong *et al.*¹⁹ that for these three substituents enhanced reactivity is not because of induced polar character but due to the enhanced stabilization of the product radical. Thus it might be possible to find an answer by looking at the group softness and electronegativity of the substituents. The high electronegativity and softness of the CHO, NO₂ and CN groups²⁷ may well be responsible for the enhanced reactivity, but more studies are necessary before we can draw any general conclusion about this.

As a final set of examples, we have taken three relatively large systems, styrene, α,β,β -trifluorostyrene and phenylacetylene. Attack upon these three systems by CCl₃ and CF₃ radicals have been studied very recently.²⁸ The Fukui function values and the atomic softness of these three systems are given in Table 2. It is clear from the table that the carbon atom attached to the phenyl ring (C²) has a very low s^0 value compared to the other olefinic carbon atom (C¹). Thus it is expected that radical attack will preferably be at the C¹ carbon atom, which conforms well with experimental observation.

We have shown in this study that regioselectivity of radical attack can be interpreted using DFT based reactivity descriptors. It has also been observed that a bond forms between the

Table 2 The condensed Fukui functions for radical attack and atomic softnesses of the two olefinic carbon atoms of styrene, α,β,β -trifluorostyrene and phenylacetylene calculated by using the B3LYP/3-21G method

Molecule	S	Atom ^a	f^0	s^0	SD ^b
H ₂ C=CHPh	2.90	C ¹	0.282	0.817	1.506
		C ²	0.030	0.087	2.236
F ₂ C=CFPh	2.92	C ¹	0.164	0.480	1.843
		C ²	0.094	0.275	2.048
HC≡CPh	2.78	C ¹	0.242	0.673	1.650
		C ²	0.008	0.022	2.301

^a C² represents the carbon atom at the phenyl substituted end of the olefin. ^b Difference in softness values between the carbon atom in CF₃ and the doubly bonded carbon atoms in the olefins.

two atoms which have the closer softness values. It is gratifying to note that the regioselectivity can be predicted from such a simple model and thus the local HSAB principle can be applied in this kind of situation too. It would of course be more compelling if the proposition of Gazquez and Méndez,¹² where the two sites are more competitive, could be tested. Similar calculations on [2 + 1] cycloadditions,²⁹ where two reactive sites are more competitive, show that the condensed Fukui functions and local softnesses work well in predicting the preferred site of attack.

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