Theoretical Study of the Reactivity and Regioselectivity of the Addition Reaction between HCl and Alkenes, Investigation of the Markovnikov's Rule

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Abstract

A theoretical study of the mechanism and selectivity of the addition reactions between HCl and alkenes were performed using DFT B3LYP/6-31G(d). Analysis of the global electrophilicityindeces shows that the alkene 1-5 behaves as a nucleophile, while HCl behaves as an electrophile. in the addition reaction of the alkenes 1-5 with HCl, the most favorable electrophile-nucleophile interaction along will take place between the most nucleophile centre of alkenes 1-5, the less substituted carbon and most electrophilic centre of HCl, hydrogen atom, in clear agreement with Markovnikov's rule. The calculation of activation and reaction energies indicates that the formations of the Markovnikov's products are favored both kinetically and thermodynamically.

Keywords: Regioselectivity, MEDT, PES, Parr function, Markovnikov rule, DFT B3LYP/6-31G(d).

1. Introduction

Many halogen compounds are easily synthesized in a highly regio- and stereoselective fashion by an addition reaction between HX and alkenes derivatives (Wang et al., 2015; Stanley et al., 1970; Shengming et al., 1999; Xiaodan et al., 2014; Haiyang et al., 2014; Graham et al., 2009; Marco et al., 2007; BruceM et al.).The hydro-halogenations of an asymmetric alkenes obeys the Markovnikov rule, the proton binds to the least substituted carbon, the reaction is regioselective. In 2008 a distortion/interaction (Ess et al., 2008; Osuna et al., 2009) was introduce by Houk (Houk et al., 2008) to explain the reactivity, this model is analogous of that proposed by Bicklehaupt in 1999 (Bickelhaupt, 1999; Fernández et al., 2014). Houk found that the activation enthalpies correlated very nicely with distortion energies. The partition of the total density of the TS geometry into two separated structure does not any physical sense within density functional DFT (Hohenberg et al., al 1964).Consequently, the energy of two Reagents cannot be correlated with the energy of TS because each of them losses the external potential created by the other Reagents. The changes in the electron density and not molecular orbital interaction are responsible

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for the reactivity in organic molecules (Domingo et al., 2014). Very recently Domingo proposed a new theory to study the reactivity in organic chemistry named Molecular Electron Density Theory (MEDT) (Ríos-Gutiérrez et al., 2015; Domingo et al., 2016).

Herein, in order to understand the effects of the substituent on the molecular mechanism and the reaction rate of the addition reaction between alkenes 1-5 and HCl, as well as the origin of the selectivities experimentally found by Markovnikov's rule (scheme 1), a theoretical characterisation of the molecular mechanism of these zw-type addition reactions is carried out within the MEDT using DFT methods at the B3LYP/6-31G(d) computational level. To this end, besides the exploration and characterisation of the potential energy surfaces (PESs) associated with the studied reactions.
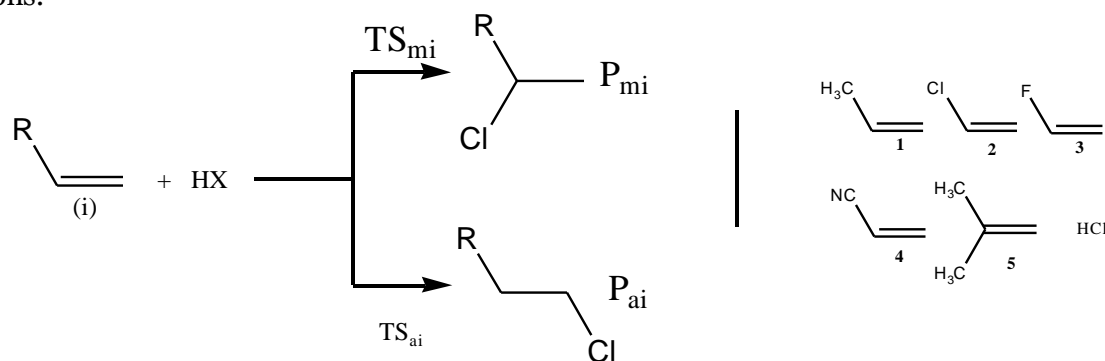
Scheme 1. Addition reaction of the HCl with alkenes.

2. Computational methods

DFT computations were carried out using the B3LYP functional (Zhao et al., 2004), together with the standard 6-31G*basis set**.** The optimizations have been realized using the Berny analytical gradient optimization method (Schlegel, 1982). All computations have been shown with the Gaussian 09 suite of programs (Frisch et al., 2009). The global electrophilicity index (Parr et al., 1999) ω, was given by the following expression, $\omega = (\mu^2/2\eta)$, in terms of the electronic chemical potential μ and the chemical hardness η. Both quantities could be approached in terms of the one-electron energies of the frontier molecular orbital HOMO and LUMO, ε_H and ε_L, as $\mu = (\varepsilon_H - \varepsilon_L)/2$ and $\eta = (\varepsilon_L - \varepsilon_H)$, respectively (Parr et al., 1983). The empirical (relative) nucleophilicity index N (Jaramillo et al., 2008), based on the HOMO energies obtained within the Kohn−Sham scheme (Kohn et al., 1965), and defined as N = EHOMO (Nu)-EHOMO(TCE). The nucleophilicity was referred to tetracyanoethylene (TCE). This choice allowed us to handle conveniently a nucleophilicity scale of positive values. Electrophylic P^+_k and nucleophilic P^-_k Parr functions (Zeroual et al., 2015; Zeroual et al., 2016; El Idrissi et al., 2016; Zoubir et al., 2017), were obtained through the analysis of the Mulliken atomic spin density (ASD) of the radical anion and radial cation of the reagents. The local electrophilicity indices were evaluated using the following expressions: $N_k = N.P^-_k$. The stationary points were characterised by frequency computations in order to verify that TSs have one and only one imaginary frequency. Intrinsic reaction coordinate (IRC) (Fukui, 1970) pathways were traced to verify the connectivity between minima and associated TSs. Solvent effects of dichloromethane were taken into account through single point energy calculations using the polarisable continuum model (PCM) developed by Tomasi's group in the framework of the self consistent reaction field (Tomasi et al., 1994).

3. Results and discussion

The present theoretical study has been divided in three parts: (1) an analysis of the conceptual DFT indices of the reageants involved in addition reaction of the HCl (hydrochloric acid) with alkenes 1-5. (2) Next, the potential energy surface (PES) associated with the addition reaction of HCl with alkenes 1-5 are explored and characterized, (3) finally a transition states geometries are analyzed.

Analysis of DFT reactivity indices of the reagents involved in the addition reaction of the HCl and alkenes 1-5.

Global DFT indices, namely the electronic chemical potential μ, chemical hardessη, electrophilicity w, and nucleophilicity N are summarized in table 1.

Table 1. Electronic chemical potential, μ, chemical hardness, η, electrophilicity, ω, nucleophilicity, N, indices and pr in eV, of HCl and alkenes 1-5.

Molecule	μ	η	w	N
1	-3.06	7.45	0.63	2.73
2	-3.58	7.10	0.90	2.38
3	-3.26	7.67	0.69	2.43
4	-4.69	6.73	1.63	1.46
5	-2.78	7.41	0.52	3.04
HCl	-4.37	9.28	1.03	0.51

The electronic chemical potential of the alkenes 1-5, -3.06, -3.58, -3.26, -4.09 and -2.78 are higher than that of the HCl, -4.37, indicating that along a polar reaction the global electron density transfer [16] GEDT will flux from the alkenes 1-5 towards the HCl.

The eletrophilicityindice of the alkenes 1, 2, 3, and 5 are 0.63, 0.90, 0.69 and 0.52 are smaller than the HCl 1.03 eV, the nucleophilicityindice of the alkenes 1,2,3,4 and 5 are 2.73, 2.38, 2.43, 1.46 and 3.04 are higher than of the HCl 0.51 eV. Consequently, it is expected that HCl participates as a good eletrophile and alkenes participates as a good nucleophile.

It has been established that along a polar reaction with non-symmetric reagents the most favourable reactive channel is that where the two-centre interaction is developed between the most electrophilic centre of the electrophile and the most nucleophiliccentre of the nucleophile. The electrophilic $P_K^+$and the nucleophilic P_K^-Parr functions have been reported as derived from the changes of spin electron density attained by a GEDT process developed from the nucleophile towards the electrophile. According to the Parr functions, the most favourable single bond formation arises between the most electrophilic and nucleophiliccentres of the reagents. The electrophilic $P_K^+$and nucleophilic P_K^-Parr functions for alkenes 1-5 and HCl are displayed in Fig. 1.
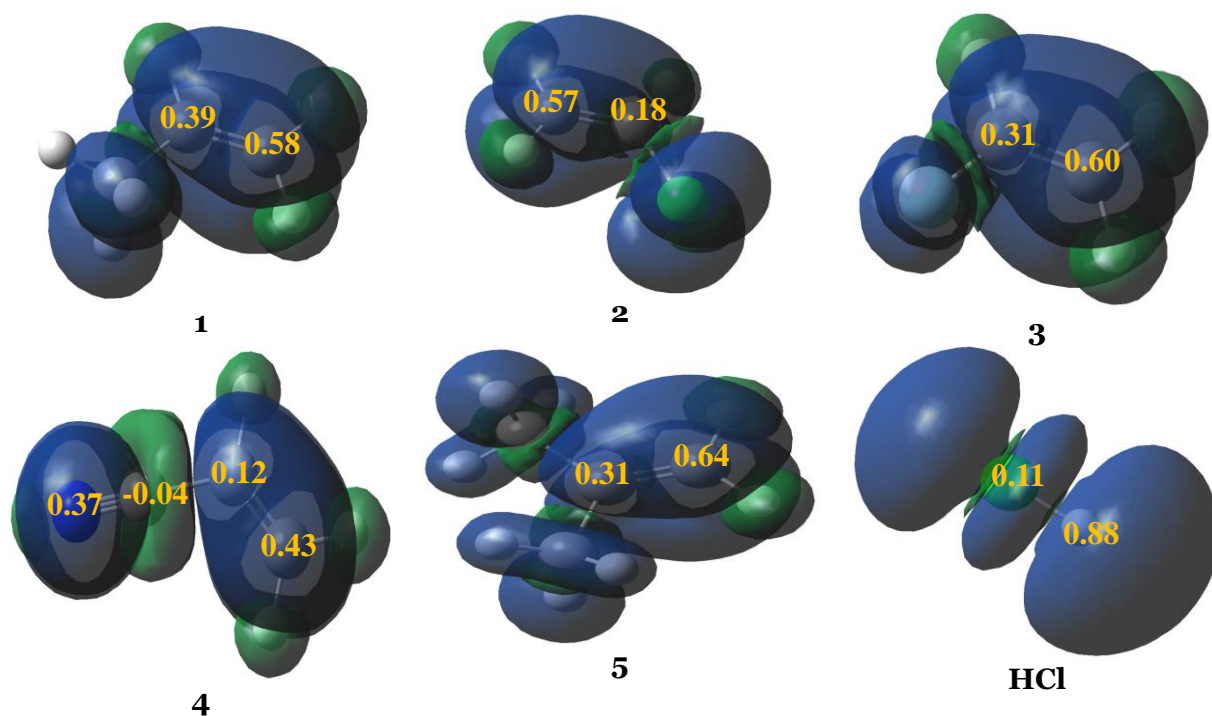
Fig. 1. Nucleophilic P_K^- Parr functions of the alkenes 1-5, and electrophilic P_K^+ Parr functions of the HCl

Analysis of the nucleophilic P_K^-Parr functions of the alkenes 1-5 indicates that the carbon not substituted is most nucleophile center of these species and this carbon presenting the maximum

value, $P_K^- = 0.58, 0.57, 0.60, 0.43$ and 0.64 respectively. On the other hand, the electrophilic Parr functions of P_K^+ of HCl indicate that the hydrogen atom is the most electrophilic centre $P_K^+ = 0.88$. Consequently, in the addition reaction of the alkenes 1-5 with HCl, the most favorable electrophile-nucleophile interaction along will take place between the most nucleophile centre of alkenes 1-5, the less substituted carbon and most electrophilic centre of HCl, hydrogen atom, in clear agreement with Markovnikov's rule.

Kinetic study of the addition reaction reaction of alkenes 1-5 and HCl

In order to investigate of the alkenes in the mechanism and regioselectivites of addition reaction between HCl and alkenes 1-5 and examining Markovnikov's rule, the value of enthalpie, the free enthalpie and entropie of the stationry points involved in this addition reaction in gas phase and water are displayed in table 2.

Table 2. The enthalpy (H a.u), the Gibbs free energy (G a.u) and entropy (S cal mol^{-1} K$^-$), computed in gas and water, for the stationary points involved in the addition reaction between the HCl and alkenes 1-5.

	gaz		water	
	G	ΔG	G	ΔG
HCl+ R$_1$	**-578.61054**	----	**-578.66422**	----
TSm$_1$	-578.601245	**5.83**	-578.627343	**23.14**
TSa1	-578.588893	**13.58**	-578.610363	**33.79**
Pm$_1$	-578.675437	**-40.72**	-578.680290	**-10.08**
Pa$_1$	-578.672874	**-39.11**	-578.676532	**-7.72**
HCl+ R$_2$	**-998.926055**	----	**-998.981309**	----
TSm$_2$	-998.907220	**11.81**	-998.930222	**32.05**
TSa$_2$	-998.895516	**19.16**	-998.913351	**42.64**
Pm$_2$	-998.987328	**-38.44**	-998.987326	**-10.05**
Pa$_2$	-998.986126	**-37.69**	-998.993794	**-7.83**
HCl+ R$_3$	**-638.554073**	----	**-638.608905**	----
TSm$_3$	-638.545601	**5.31**	-638.569715	**24.59**
TSa$_3$	-638.523234	**19.35**	-638.542904	**41.41**
Pm$_3$	-638.624902	**-44.44**	-638.629000	**-12.60**
Pa$_3$	-638.616136	**-38.94**	-638.620577	**-7.32**
HCl+ R$_4$	**-631.564522**	----	**-631.624168**	----
TSm$_4$	-631.536062	**17.85**	-631.554284	**43.85**
TSa$_4$	-631.533641	**19.37**	-631.552620	**44.89**
Pm$_4$	-631.618766	**-34.03**	-631.625576	**-0.88**
Pa$_4$	-631.616462	**-32.59**	-631.631941	**-4.87**
HCl+ R$_5$	**-617.939221**	----	**-617.949274**	----
TSm$_5$	-617.902622	**22.96**	-617.933615	**9.82**
TSa$_5$	-617.879759	**37.31**	-617.901448	**30.01**
Pm$_5$	-617.965970	**-16.78**	-617.953840	**-2.86**
Pa$_5$	-617.960549	**-13.38**	-617.964097	**-9.30**

The gas-phase activation with the two competitive channels are 5.83 (TSm$_1$) and 13.58 (TSa$_1$) kcal/mol, the reaction being exothermic by 40.72 and 39.11 kcal/mol, consequently, it can be considered irreversible. This energy result is formed by kinetic and thermodynamic control.

The activation free energies with the competitive channels of the reaction between HCl and R$_2$ are 11.81 (TSm$_2$) and 19.66 (TSa$_2$) kcal/mol, indicating that the Pm2 is kinetically favored, this reaction being exothermic by 38 Kcalmol-1, consequently, this reaction can be irreversible.

The activation Gibbs free energy of the stationary points involved in this addition reaction between HCl and R3 are 5.31 (TSm3) and 19.35 (TSa3) kcal/mol, the formation Gibbs free energies of the products are 44.44 (Pm3) and 38.94 kcal/mol (Pa3), the formation of the product Pm3 is

strongly exergonic than Pa3 by 5.50 kcal/mol, consequently the formation of the product Pm3 is kinetically and thermodynamically very favored.

The activation Gibbs free energies of the stationary points involved in reaction HCl and R4 are 17.85 (TSm4) and 19.37 Kcal/mol(TSa4), this energy result indicate that the formation of the product Pm4 is kinetically favored, in addition the reaction being exothermic by 34.06 (Pm4) and 32.59 kcal/mol (Pa4) is thermodynamically favored too.

The activation Gibbs free energies associated with TSm5 and TSa5 are 22.96 and 37.31 kcal/mol respectively, the reaction being exothermic by 16.78 (Pm5) and 13.38 kcal/mol (Pa5), this energy result indicate that the formation of the product Pm5 is kinetically and thermodynamically favored in good agreement with Markovnikov's rule.

Inclusion of solvent effects of water increases the gas phase activation energies by 17.31 (TSm1), 20.21 (TSa1), 20.24 (TSm2), 23.48 (TSa2), 19.28 (TSm3), 22.06 (TSa3), 26.00 (TSm4), 25.52 (TSa4), 13.14 (TSm5) and 7.03 (TSa5) kcal/mol and slightly decreases the exothermic character of the reaction by 30.64 (Pm1), 31.39 (Pa1), 25.84 (Pm2), 29.86 (Pa2), 31.80 (Pm3), 31.62 (Pa3), 33.15 (Pm4), 18.72 (Pa4), 13.92 (Pm5) and 4.08 (Pa5), these effects are consequence of the better salvation of addition reaction between HCl and alkenes in this polar solvent. In this case, while the Markovnikov's regioselectivity is increased

The lengths of the forming bonds in the geometries of the TSs involved in the two competitive reaction channels in water are also included in Fig. 2. A comparison of the lengths of the C−C forming bonds obtained in gas phase and water indicates that there are no significant differences. The most favorable TS-m1, TS-m2, TS-m3, TS-m4, TS-m5 and TS-m6 becomes slightly more asynchronous, since the H−C distance increases by 0.1 Å. Consequently, the inclusion of solvent effects of water modifies neither the relative energies nor the C−Cl single bond formation at the TSs.
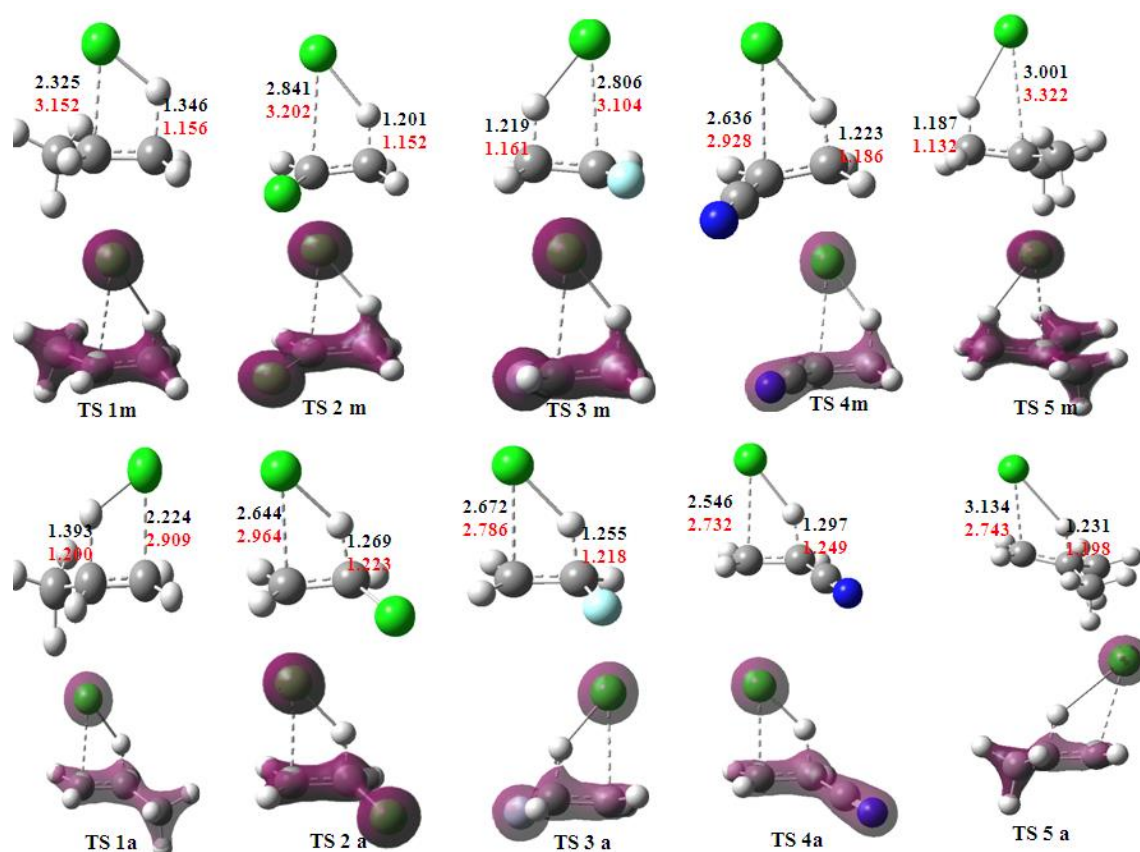

Fig. 2. DFT/6-31G(d) optimized density map and structures of the TSs of the addition reaction between the HCl and alkenes 1-5. Lengthsaregivenin Angstroms.

4. Conclusion

The addition reaction of HCl with ethylene 1-5 has been studied within the MEDT through DFT calculations at the B3LYP/6-31G(d) computational level. The obtained results are supported by the combination of the analysis of the reactivity indices at the ground state of the reagents, derived from the conceptual DFT, the exploration of the energies associated with this addition reaction along the corresponding reactive channels. Analysis of the nucleophilic P_k^- Parr functions allows characterizing the C carbon atom as the most nucleophilic centre of 1-5, in clear agreement with the regioselectivity found in Markovnikov's rule. An exploration of the energies associated with this addition reaction indicates this addition reaction is high regioselectivity and Markovnikov's products are kinetically and thermodynamically favored.

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