

Practice # 5 Battle of speed SET vs HAT, hydrogen abstraction of phenol with hydroperoxyl radical.

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Abstract

This report studied and compared two mechanisms for the abstraction of hydrogen from phenol with hydroperoxyl radical HAT and SET, with a normal procedure we calculate the transition state and ΔG^\ddagger for HAT, in the case of SET we calculated ΔG^\ddagger indirectly using the Marcus theory, and calculated the rate constant for each one, considered a fisiological pH to know the fraction mol of phenol and phenoxide in solution, and was determined that SET is the mechanism predominant for the abstraction of hydrogen via SPLET.

Keywords: *Hydrogen abstraction, SET, HAT, Marcus theory.*

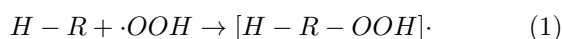
1 Introduction [1][2]

The reaction mechanism antioxidants such as phenolic compounds can be divide into two groups in mechanisms of one step or more than one.

Single Step Mechanisms

Radical Adduct Formation (RAF)

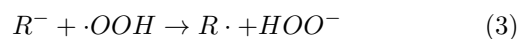
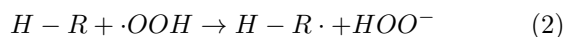
This reaction consists in the formation of an adduct radical, this usually is carotenoids, where the radical is stabilized by the delocalization of electron through the unsaturated long-chain and rings.



Single Electron Transfer (SET)

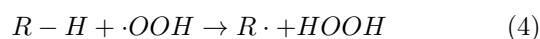
Consist of the transference of one electron from the antioxidant to radical which converts into an anion with low reactivity than radical.

This reaction can be with the antioxidant (2) or the anion of the antioxidant (3).



Hydrogen Atom Transfer (HAT)

This is the transfer of hydrogen atom from antioxidant to the radical a making it into a neutral molecule and forming a stable radical with the antioxidant.



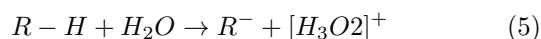
Proton Coupled Electron Transfer (PCET)

The equation (4) is the same equation with PCET with the difference that this mechanism has a parallel step transferring a proton and electron and the same time.

Multiple Step Mechanisms

Sequential Proton Loss Electron Transfer (SPLET)

This reaction consist in two step with the first is the deprotonation of the antioxidant by solvent (5) and SET reaction (3)



HAT mechanisms can be described and get the ΔG^\ddagger but in the case of SET mechanism can not calculate directly, the reason for this does not exist the transition state.

Marcus Theory [3]

The free energy of electron transfer is described in (6).

$$\Delta G^\ddagger = \frac{\lambda}{4} \left(1 + \frac{\Delta G^0}{\lambda} \right) \quad (6)$$

Schematically we can see the energy of reactive and products as two paraboles where the energy activation ΔG^\ddagger is the difference between the energy of reactants and the intersection between both paraboles.

Where λ is the reorganization energy (7), this is the energy to give to react to get the same nuclear configuration of products without transferring the electron.

$$\lambda = \Delta E - \Delta G \quad (7)$$

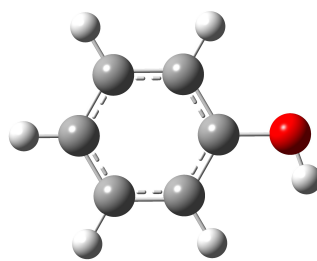
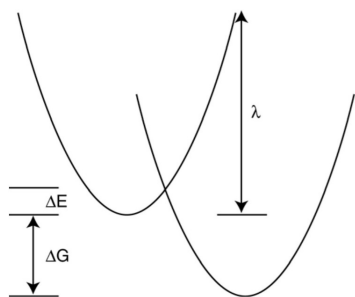


Figure 1: Phenol.

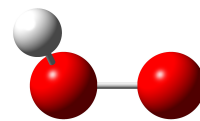


Figure 2: Hydroperoxyl radical/anion.

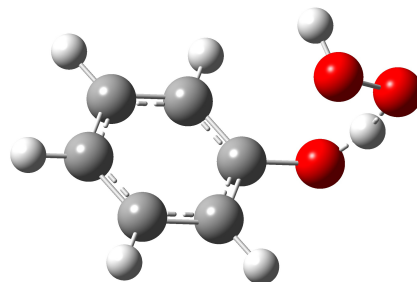


Figure 3: Transition state.

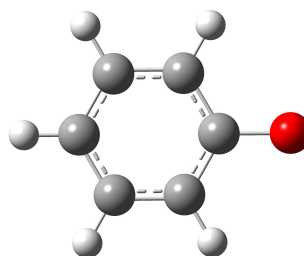


Figure 4: Hydroxyphenyl radical/anion.

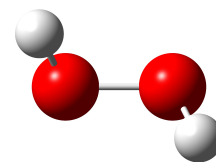


Figure 5: Hydrogen peroxide.

Mechanism contribution [4]

To know which mechanism predominates is important to consider the state of the reagent because may or may not be protonated and this favors different mechanisms as SPLET when species is an anion and neutral to HAT.



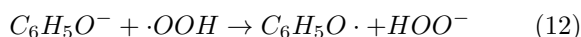
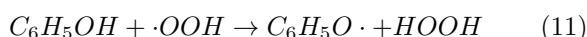
For dissociation reaction of monoprotic acids (8) the equation of fraction mol for the species HA and A^- are shown in (9) and (10)

$$\chi_{HA} = \frac{[H^+]}{[H^+] + k_a} \quad (9)$$

$$\chi_{A^-} = \frac{k_a}{[H^+] + k_a} \quad (10)$$

Hydrogen abstraction reactions from phenolic compounds are important because are antioxidant, and know information about the mechanism used to inhibit radicals are very essential to learn more.

To know which mechanism are predominant in these reaction, we model the reaction of phenol with Hydroxyphenyl-radical and model by HAT (11) and SET (12).



Materials and methods

The modeling of the systems C_6H_5OH , $C_6H_5O\cdot$, $C_6H_5O^-$, transition state (TS), $HOOH$ and $HOO\cdot$ were performed with gaussView these are shown in Figures 1-5.

The calculations were performed with a laptop with an i7-8750H processor with 8GB of RAM.

The transition state was run using the following configuration.

```
% nprocshared=4
% mem=1500MB
# opt(calcfc,ts,noeigen) freq=noraman
scrf=smd 6-31+G(d,p) iop(1/8=3) m062x
```

NOTE: The transition state was re run with the following command to converge correctly `# opt(readfc,ts,noeigen) geom=check guess=check freq=noraman scrf=smd 6-31+G(d,p) iop(1/8=3) m062x`

For reactives and products we use the following configuration.

```
% nprocshared=4
% mem=1500MB
# opt freq scrf=smd 6-31+G(d,p) m062x
```

Results

Table 1 Values of G in Hartree for each system and Electronic energy* for systems used for SET.

Species	G (H)	E (H)
C_6H_5OH	-307.287	-
$HOO\cdot$	-150.866	-150.857
TS	-458.120	-
$HOOH$	-151.500	-
$C_6H_5O\cdot$	-306.651	-306.710
$C_6H_5O^-$	-306.825	-306.888
HOO^-	-151.031	-151.006

* For species used to model SET we get the value of electronic energy, in the case of the reagents we get the value of the optimization (last step of calculation which are the optimization of geometry), and the value of electronic energy of the first point of the products (which are the calculation of energy without optimization) with these are calculated the reorganization energy.

To calculate the ΔG^\ddagger for SET we calculate λ , for this we calculate the ΔG and ΔE of reaction (12))

Using the following equation.

$$(\Delta G_{prod} - \Delta G_{reac}) * 627.509 \quad (13)$$

Giving that $\Delta G = 5.117 \text{ kcal/mol}$ and $\Delta E = 18.670 \text{ kcal/mol}$ we can calculate λ but still, we need to make a fix, the calculation for OOH solvation is poor with only SMD so we add a correction using supermodel this is a correction of 7 kcal/mol , giving a corrected value of $\Delta G = -1.882 \text{ kcal/mol}$ now using (7) was calculated the reorganization energy $\lambda = 20.552 \text{ kcal/mol}$.

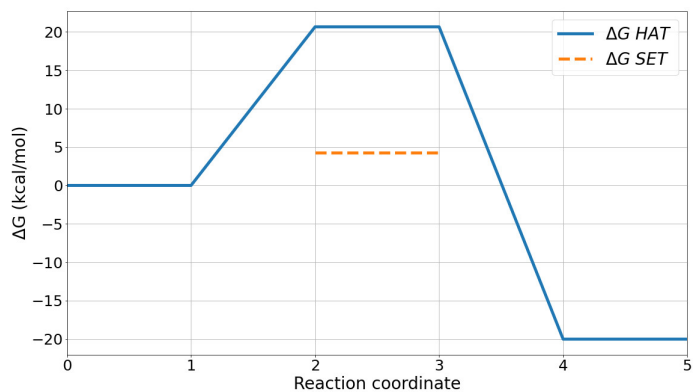
Using Marcus equation (6) we get the $\Delta^\ddagger = 4.240238719 \text{ kcal/mol}$.

Profile reaction of reaction with HAT was build with table 2.

Table 2 ΔG for reaction profile of HAT

React coord.	ΔG
0-1	0
2-3	20.662
4-5	-20.026

Graph 1 Reaction profile for HAT

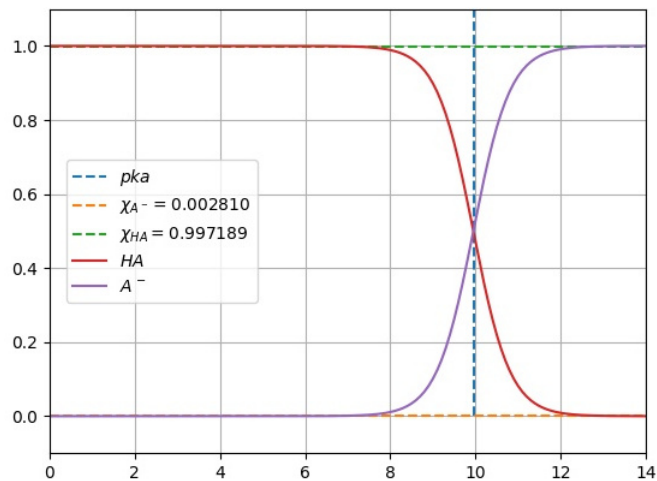


Also using the ΔG^\ddagger obtained from HAT mechanism and with Eyring equation we calculated the rate constant, consider $k = 1$ and $\sigma = 1$, and also make a correction for standard condition 1M used by gaussian with $(RT/P \approx 24)$ and consider Benson correction ($\Delta G^\ddagger - 2.55 \text{ kcal/mol}$), for calculation of the rate constant for SET ($RT/P = 1$) because Marcus theory gives the correct units.

We obtain that $K_{SET} = 3.40 \times 10^9$ and $K_{HAT} = 8.02$

Also, was considered the molar fraction of the species in physiological pH (7.4) in this pH the phenol is protonated as can be appreciated in graph 2 made with (9) and (10).

Graph 2 Species distribution diagram of phenol



Considering the rate constant and the current fraction, and was calculate a new rate constant, $\chi_{HA} \cdot K_{HAT} = 7.999$ and $\chi_{HA} \cdot K_{SET} = 9.55 \times 10^6$.

Discussion

With reaction profile we can compare the activation energy of both paths, where the ΔG^\ddagger of SET calculated with Marcus theory show a lower barrier against the HAT, this tells us that **energy required to transfer an electron**

is less than transfer a hydrogen atom from phenol to Hydroperoxyl radical.

Comparing the rate constant of both mechanisms it is very obvious the difference, where the SET rate constant is 9 orders of magnitude bigger than HAT rate constant, consider this we know that **SET mechanism is faster than HAT.**

The pH plays an important role for the predominant mechanism because SET occurs as a step of SPLET when the antioxidant is in anionic form, seeing the graph 2 we can know that in $\text{pH} > \text{pKa}$ the mechanism predominant will be SET, but under that, we can think that predominant mechanism is HAT, but when χ_{A^-} and χ_{HA} are multiply by his rate constant, we can observe that SET rate constant is 6 orders bigger than HAT, **this confirms that the predominant mechanism for the abstraction of the hydrogen atom from phenol by the hydroperoxyl radical is via SET.**

References

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