Organic Chemistry-2

Semester-2, CBCS

Course: CEMA CC-2-3-TH

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Recommended texts:

Elimination reactions:

E1 reaction:

The stepwise elimination of H-X from the vicinal carbons (1,2) of a suitable substrate such as an organohalide or an alcohol with the involvement of a carbocation intermediate is the E1 elimination, as we have seen before.

Rate law and relation with $S_{N}1$:

E1 reaction's **RDS is the heterolytic dissociation of the C-X bond**. Whatever happens after that, does not show up in the rate expression. Therefore, we have the following rate law for the E1 elimination of $t$-butyl bromide into isobutene:

$$\text{Rate} = k_{1} [t-\text{BuBr}]$$

i.e. the reaction is first order with respect to the substrate.

Instead of abstracting the $\beta$-proton from the carbocation, ethanol might also have attacked the electrophilic carbon atom directly. In that case, after the proton transfer, we would have got an ether. This is not elimination, but substitution:

Clearly, E1 and SN1 reactions share a common RDS and common rate expression.

It is clear then that like the SN2 and E2 pair, SN1 and E1 reactions also go hand in hand and whenever there is SN1, there is bound to be some E1 as well. It is also clear that formation of a *relatively stable carbocation* and a reaction medium conducive for ionisation are a pre-requisite for these processes to occur.
Elimination reactions:

E1 reaction: E1 and SN1 reactions share a common RDS and common rate expression.

To validate this, the following reaction was done with three different substrates (varying the leaving group X) under identical reaction condition:

\[
\text{R-X} + \text{H}_{2}\text{O, EtOH, heat} \rightarrow \text{E1 products, 37\%} + \text{SN1 products, 63\%}
\]

It was observed that - i) the rates of the reaction were widely different for the three substrates but ii) for all three, the product distribution remained the same.

The rate varied in the following manner: R-I > R-Br > R-Cl.

Rationale: This order is at par with the E1 mechanism where the C-X bond breaks in the RDS. The C-I bond, being the weakest of the three, breaks most easily and the R-I reacts fastest.

The product distribution, i.e. the relative amounts of the E1 and the SN1 products, were same for all three.

Rationale: This indicates that the product formation steps are independent of the nature of the nucleofuge. For an irreversible reaction, this can only be true if the product-determining steps occur after the RDS is over. In that case, all four products will form from a common precursor, i.e. the carbocation intermediate and irrespective of the starting organohalide the SN1:E1 product ratio will be the same.

How much each of SN1 and E1 product would form, that would of course depend upon the relative energies of the respective TSs for the two product-determining steps.

As SN1 products are found to dominate the product mixture in the example cited, we have to place the TS for the nucleophilic capture of the carbocation at a lower energy level than the TS for loss of the \(\beta\)-proton.

The adjacent energy profile diagram is instructive:

It is evident that E1 and SN1 reactions generally occur together leading to a mixture of products. Only by carefully modulating the reaction conditions, one can be made to dominate the other.
Elimination reactions:

E1 reaction: Dehydrations of alcohols: An E1 reaction:
Recall from our discussions in E2 reaction that alcohols are really bad substrates for elimination because hydroxide is poor leaving group, as it is a strong base and the C-O is a strong bond (BDE is high).

Alcohols, however, can be made to undergo elimination reaction through the E1 mechanism.
The reaction is carried out in acidic medium where the hydroxyl group is first protonated and converted to a better leaving group -OH₂.

Why does protonation improve the leaving group ability of the -OH group?

Consider the following:

\[
\text{R-OH} \xrightarrow{\text{H}^+} \text{R}^+ + \text{HO}^- \\
\text{C-O bond stronger} \\
\text{conjugate acid } \text{H}_2\text{O, } pK_a \text{ 15.7} \\
\text{R-OH} \xrightarrow{\text{H}^+} \text{R}^+ + \text{H}_2\text{O} \\
\text{C-O bond has weakened} \\
\text{conjugate acid } \text{H}_3\text{O}^+, pK_a \text{ -1.5} \\
\]

Therefore, H₃O⁺ is a stronger acid than H₂O, implies that HO⁻ is a stronger base than H₂O and H₂O is a better leaving group than HO⁻

Let us consider the following example of E1 reaction of 2-propanol to propene:

The rate expression for this reaction is: \[ \text{rate} = k [\text{ROH}][\text{H}^+] \]

i.e. first order w.r.t. both the alcohol and the acid, overall second order.

Clearly, the RDS involves the dissociation of the C-O bond in the protonated alcohol and the rate is proportional to the concentration of the same, which, in turn, depends upon the concentrations of acid added and the alcohol present.

\[ \text{rate} = k'[\text{ROH}_2]^+ \]

and \[ [\text{ROH}_2]^+ = K [\text{ROH}][\text{H}^+] \]

where \( K = \frac{[\text{ROH}_2]^+}{[\text{ROH}][\text{H}^+]} \) for the eqn. \( \text{ROH} + \text{H}^+ \rightleftharpoons [\text{ROH}_2]^+ \)

Therefore, \[ \text{rate} = k [\text{ROH}][\text{H}^+] \]

where \( k = kK' \)
Elimination reactions:

E1 reaction: Dehydrations of alcohols: An E1 reaction:

Acid-catalyzed dehydration of 2-propanol to propene:

\[ \text{Me}_2\text{C} - \text{OH} \xrightarrow{\text{H}_2\text{SO}_4, \text{heat}} \text{Me}_2\text{C} = \text{CH}_2 \]

rate = \( k [\text{ROH}][\text{H}^+] \)

Clearly, the RDS involves the dissociation of the C-O bond in the protonated alcohol.

The reaction proceeds through the following pathway, involving three steps where the second step is the RDS:

1. protonation of alcohol, acid consumed
2. loss of water from the protonated alcohol, carbocation generated, slow step
3. loss of \( \beta \)-proton, alkene formed, acid regenerated

Note that the whole reaction is reversible, in the forward direction it is the dehydration of alcohol to alkene, and on the reverse direction it is the hydration alkene to alcohol.

The reaction is catalytic in acid as at the end of the reaction acid is regenerated.

To minimize the SN1 reaction during the E1 process, the acid that is used must have a non-nucleophilic counter-ion (i.e. the CB). Preferred choices are H\(_2\)SO\(_4\), KHSO\(_4\) or H\(_3\)PO\(_4\), where the conjugate bases are resonance-stabilised and essentially non-nucleophilic:

![Resonance-stabilised and essentially non-nucleophilic cB](image)

If we use HCl or HBr, then the chloride or iodide ions would rapidly attack the carbocation formed and SN1 products would form.

If the CB is nucleophilic, this will happen:

If \( X = \text{Cl} \) and the CB is non-nucleophilic, no nucleophilic attack will occur.

Study Guide to Organic Chemistry
- Saha et al. Volume 2 (ISBN 9788192669588)
Elimination reactions:

E1 reaction: Dehydrations of alcohols: An E1 reaction:

Acid-catalyzed dehydration of 2-propanol to propene:

\[
\text{Me}_3\text{C} = \text{Me} \xrightarrow{\text{H}_2\text{SO}_4, \text{heat}} \text{Me}_2\text{C} = \text{C} \text{Me} \]

\[
\text{rate} = k [\text{ROH}][\text{H}^+]\]

Clearly, the RDS involves the dissociation of the C-O bond in the protonated alcohol.

The reaction proceeds through the following pathway, involving three steps where the second step is the RDS:

\[
\text{Me}_3\text{C} \text{OH} \xrightarrow{\text{H}^+, \text{fast}} \text{Me}_3\text{C} = \text{OH}_2 \xrightarrow{\text{H}_2\text{O}, \text{slow}} \text{Me}_3\text{C} = \text{H} \xrightarrow{\text{H}^+, \text{fast}} \text{Me}_3\text{C} \text{H}_3\text{O}^+ \]

The energy profile diagram of the dehydration reaction is outlined below:

in the proton abstraction step, water is acting as the base.
Elimination reactions:

E1 reaction: Effect of substrate structure:

The RDS of the E1 mechanism involves the formation of a carbocation.

It is an endothermic process, so the RDS TS mimics the carbocation closely.

As the carbocation becomes more stable, so does the RDS TS and the reaction becomes faster.

Therefore, E1 reaction is more favourable for those substrates that can afford relatively stable carbocations.

On the other hand, substrates that cannot produce such an intermediate are much less reactive in E1.

Case in point is the relatively facile dehydration of tertiary alcohols compared to secondary, and more notably primary alcohols which require much harsher conditions to undergo dehydration.

It is also a possibility that primary alcohols dehydrate under acidic condition by an E2 mechanism and do not opt for the E1 mechanism at all!

In fact, tertiary alcohols are so sensitive to acid that the reaction flask must be washed with ammonia solution to make it acid-free before using it with such substrates.

E1 Reaction: rearrangement:

As a full-blown carbocation is involved in E1, the reaction is sometimes plagued by the problem of rearrangement that leads to a number of undesired products.

This is particularly problematic if the initially formed carbocation rearranges faster to a more stable counterpart than losing the \( \beta \)-hydrogen:
Elimination reactions:

E1 reactions: Regioselectivity

We have already seen that the E1 reaction can be regioselective, as in the following example:

Among the alkenes, the more-substituted, Zaitsev alkene is the major product of this E1 reaction.

Just as in E2, it is not because the Zaitsev product is thermodynamically more stable, but because the TS leading to the more-substituted Zaitsev alkene is more stable than the TS leading to the less-substituted Hofmann alkene.

To understand why this is so, consider the following scheme:

We need to understand that the regioselectivity of the elimination reaction is controlled by the relative stabilities of the TSs associated with the proton abstraction steps.

It depends upon whether the β- or the β'-hydrogen would be abstracted from the carbocation by any suitable base present, here the base is most likely the solvent.

The following energy profile diagram is instructive:

As the scheme demonstrates, picking off the β-hydrogen would afford the Zaitsev product and removal of the β'-hydrogen would lead to the Hofmann product.

Abstraction of proton from the β-position is associated with a lower activation energy barrier because the corresponding TS is more stable than that associated with β'-proton abstraction. Both the TSs has some alkene-like nature and TS$_{2P}$ is therefore more stable than TS$_{HP}$ as the former has a more substituted partially formed double bond, leading to the major elimination product.

Notice carefully that you have the option to change the regioselectivity of the E2 reaction of an alkyl halide in favour of the Hofmann product by changing the base to a sterically more demanding one. In contrast, the E1 pathway does not offer a similar level of control over the regiochemical outcome. In an E1 process, there is no direct way to favour the less-substituted alkene.
Elimination reactions:

E1 reactions: Stereoselectivity

Like E2 reactions, E1 reactions are also stereoselective and the stericly less crowded diastereomer of the product alkene is generally favoured. Again, not because it is thermodynamically more stable than its more crowded diastereoisomer, but because the TS leading to the formation of the less crowded alkene is more stable than that leading to the formation of the more crowded alkene.

The geometry of the product is determined at the moment that the proton is lost from the intermediate carbocation.

The new \( \pi \) bond can only form if the vacant \( p \) orbital of the carbocation and the C-H bond that is breaking are aligned parallel. Recall the anti-, or in some cases, the syn-periplanar geometry between the C(\( \beta \))-H and the C(\( \alpha \))-X bonds that is required for E2 elimination.

In the example shown there are two possible conformations of the carbocation with parallel orientations, but one is more stable than the other because it suffers less steric hindrance.

The same is true for the TSs on the route to the alkenes - the TS leading to the E-alkene is lower in energy, and more E-alkene than Z-alkene is formed.

The process is stereoselective because the reaction chooses to form predominantly one of two possible stereoisomeric products.