

Lecture 17B • 11/03/11

[lab reports]

We have the example of acetic acid reacting with sodium hydroxide. We know that acetic acid is a weak acid; we can know that by its pKa value. pKa is the negative base 10 log of Ka. I want you to have a sense that if you have an acid which is weak, which means it doesn't want to dissociate, which means its K is really tiny, tiny meaning less than one, that it's going to have a larger pKa value the smaller that value of K that you have. Weak acid means low dissociation, which means K less than one, which means a pKa that is greater in value. If you say that K is less than 1, that also means that delta G is greater than zero; we use the delta G = -RT ln K equation to get that.

Here's the example: what if we all this neutralization to occur? Let acetic acid be deprotonated by sodium hydroxide? Knowing that poor dissociation means poor equilibrium constant means an increase in delta G, we could draw a reaction progress diagram of this form. Here's the story we could tell: acetic acid, being a weak acid, would, on its own, only want to dissociate to a very small extent. Very very roughly, you say that 1% of it dissociates on its own. If you use a strong base like sodium hydroxide, at least in principle, you can force this to dissociate, force it to become neutralized. But if you force this reaction to completion, if we make it go 100% forward, then we've got three different problems: one, we have products, but no reactants – Q would be undefinable at that point because you'd be taking something and trying to divide it by zero. Just short of that, you'd have an enormous Q – too many products compared to reactants. Since Q is greater than K, the reaction would want to shift back to K. Another way of thinking about it is if you only have products, then the only possible reaction is the reverse dissociation of acetic acid. Up above I've written the equation for neutralization, but there's an equilibrium that's still going on despite that neutralization; there's a balance between how much acetic acid and acetate that you have in solution. This is really the equilibrium that we're talking about. If you only have products, if you only made acetate, then the only direction possible in the equilibrium is for it to go backwards to make acetic acid. The third way of thinking about it is to use this reaction progress diagram, to say: alright, if you did force the reaction to completion, energetically that's not terribly favorable; you're pushing it uphill in energy, so it would want to fall back downhill in energy in order to re-establish equilibrium, be at its lower-energy point.

[3 definitions of equilibrium: concentrations, rate, energy]

If acetic acid is forced to fully dissociate: 1) there are only products, no reactants, so Q – it's undefinable – it's [effectively] greater than K; 2) only the reverse reaction for the dissociation of acetic acid is possible, again because there's no reactants, so you can't have the forward rate of reaction; 3) the reaction is driven to a higher potential energy. Because of this, acetate is going to react. Since you made water as a product, it will react with water; when it reacts with water, it makes hydroxide again, which means the resulting solution is basic. This happens even if you have exactly the same number of moles of acetic acid and base, and that's why neutralized is not the same thing as neutral. Since the equilibrium for acetic acid has been forced to the right, too far towards products, acetate will react with water to reform acetic acid and re-establish equilibrium; therefore, neutralized does not mean that you're going to have a neutral solution.

[acid-base reactions in extraction lab]

I want to talk about structural effects on the acidity of compounds. Let's compare these five compounds: ethane (pKa 50-60), ethyne (25), ethanol (16), acetic acid (4.65), trifluoroacetic acid (0.23)

In water, it's actually not possible to calculate the pKa, because this is such a weak acid that if you were to force the proton to come off and then throw it into water, it would just destroy the water and make hydroxide; therefore all that would have left floating around in solution is hydroxide, so you can't measure the strength of the compound directly.

Let's talk about the different reasons why we have these different kinds of reactivity.

Let's tackle the first two first – the difference between ethane and ethyne. In order to be able to talk about this difference, let's look at the structures of the products that we would get if the proton came off. If we imagined that ethane dissociated, we'd make an ethyl carbanion; if we allow ethyne to dissociate, then we will make the ethynyl carbanion. What is really, in some ways, the only difference between these two ions? What's different about the two carbons that are there? What's the hybridization of the first compound's carbon? How many hydrogens are really there? Three. I might have written in only one of them, but there's no other symbol here on this carbon, so I wrote the hydrogen in just for emphasis. Way back when we covered line structures, I had said there are exceptions to how you draw line structures. One of them could be just like this – where you want to show that there's a hydrogen there so that you can write a mechanism arrow to go with it. But, there are still three hydrogens there, so it's sp³-hybridized; the anion you get, because you have a lone pair, that lone pair does affect geometry, does get counted in VSEPR theory, does therefore get counted in hybridization, it's still sp³ hybridized. What about the alkyne? sp hybridization.

There is this phrase that's often used – s character – which means the percentage of s orbital in a hybrid. In the case of sp^3 , it's 25% s character; in the case of sp , it's 50% s character. Why does this matter? Because in atoms that have multiple electrons, s and p orbitals are different energy from each other – s orbitals are lower in energy than p orbitals. If you have a hybrid that's made up of more s orbital, you're going to have a hybrid that's effectively closer to the nucleus, which means the electrons in it are going to be lower in energy – versus the sp^3 that's only 25% s, it's much more like a p orbital in its configurations, which means the electrons are held a bit further away from the nucleus, which means that's a higher-energy orbital. sp^3 versus sp , the electrons in those orbitals are in different energies. Let's start with that thought: in polyelectronic systems, s orbitals are lower in energy than p orbitals. Hybrids that are composed of a greater percentage of s orbital – or we could say more simply greater s character – are therefore lower in energy. So, electrons in an sp orbital are lower in energy than sp^3 .

Let's make a graph that please realize I'm going to show you something that's misleading, because I'm going to start from the same energy level. These are not the same molecule, ethane and ethyne. To be a bit better, I won't show them starting on the same level, but I'm going to put them on the same place on an energy scale, I'm going to do this. They have these tiny tiny pKa values, that means these are endergonic processes. Instead of reaction progress diagram, let's write a reaction coordinate diagram. I'm going to write two of them side-by-side. I'm going to go ahead and do it in terms of delta G since we're using equilibrium constants. Here's what effective I want to show: that if the electrons end up in a lower-energy orbital, in the triple bond case, then that's going to mean a smaller delta G, closer to being negative. If you have a smaller delta G, that means that forward process is more likely, which is why it has a lower pKa, a higher equilibrium constant. If you stabilize the product, you make it easier to form. If you stabilize it and make it easier to form, that means, in this case, more acidic, coming from the original compound.

If you're doing something that makes it easier for it to stick around, you're making it easier for the product to form. This is actually a very very bad comparison, because I'm making these two molecules appear to be at the same energy level, but they're not, because they're not isomers, but what I'm trying to show is that if you made that comparison, then you would see that the product from a triple bond would be comparatively at a lower energy than the product from the single bond. That lowering in energy, that lowering in delta G, makes it less positive, makes it less bad for it to happen, so, effectively, by that sp orbital being there instead of sp^3 , the ion's more stable. Because it's more stable, it's easier to form, and so to come from the acid to make that ion is easier, that means greater equilibrium constant, more acidic, lower pKa. For a hydrogen on a triple bond, that's why a pKa of 25 versus the 60 that you get for an alkane.

Structural effects that stabilize a product make it easier to form, which in this case means the original acid dissociates more easily, which means we have lower pKa.

Let's use the same reasoning to look at the difference between ethane versus ethanol. Just on the basis of electronegativity, which of these intuitively would seem to make more sense to occur? In other words, which atom is more electronegative: carbon or oxygen? Oxygen. If everything else is equal here except for the fact that oxygen's there, oxygen must be what is causing this compound to be much more acidic – 60 for the pKa of ethane versus 16 for the pKa of ethanol, that's billions and billions of times more acidic. That's because, since oxygen is more electronegative, it is better able to tolerate that negative charge. If it's better able to tolerate the negative charge, that makes it easier for the hydrogen to come off, for that negative charge to form, which is why ethanol's more acidic. This is what's called an inductive effect, where you have electron density that's being pulled away by something that's electronegative, that's called induction.

Let's look at one last effect: the difference between ethanol and acetic acid. Just having the two oxygens there is part of the reason [that acetic acid is more acidic than ethanol], because if one oxygen can pull electron density away, then two oxygens does an even better job. But, it's not the only thing causing this acetate ion to form more easily. What else is going on here? What is going to happen to the lone pair that's on that oxygen; does it remain on that oxygen? No. This is just one of two possible resonance structures. That's exactly the point: that since that negative charge is delocalized, it's effectively stabilized. If I put even a double-bonded oxygen someplace else like one carbon further away on the molecule, it will have a small inductive effect, but it will still effectively be an alcohol, that molecule. It's pKa is roughly 13, certainly not as low as 4. That extra stability caused by spreading that negative charge around makes acetate easier to form – it's called the resonance effect. If the negative charge formed by dissociation can be delocalized, it is effectively easier to form the anion, meaning the parent acid is more acidic.

If we go back to the list of molecules I had, look at the last one on the list: trifluoroacetic acid. Almost has a negative pKa. It's got both inductive and resonance effects taking places at the same time; it's a carboxylic acid, it has the same kind of resonance that acetic acid does, but the addition of the fluorines, even though they're one more position away, since fluorine's that electronegative, it has enough of a tug across the molecule that it's the same inductive effect we had for ethanol: pull electron density away from that oxygen-hydrogen bond, which makes the oxygen-hydrogen bond easier to dissociate, when means the compound's more acidic.

[introduction to aromaticity]

Resonance is theoretically possible for ethyne, except the structures would be so terrible that, no, resonance really doesn't have any place there. Since you only have single bonds in ethane, there can't be resonance there. Since you only have carbon versus carbon, they're equal in electronegativity, and because we have the same type of hybridization of one carbon with another, there's also the same electronegativity. Technically, if you have an sp^2 - versus an sp^3 -hybridized carbon, there might be a slight imbalance in electron density, but it's so small that that in itself doesn't have a significant effect – not as much as the fact that you have a different hybridization itself.

What is all of this for? To lead us up to the point where we are going to begin synthesis. Where, if you have an alkyl halide, you can perform a reaction where you can turn it into an alcohol, which, once reacted with the right kind of reagent, could be converted into a carboxylic acid, for example, that if flooded with an alcohol and acid can be turned into an ester. I can start with some small molecule and do a series of reactions that I could build up to a larger molecule. Each reaction, then, you have a set of things that you've gotta worry about. One, what is the synthetic utility of that reaction; what is the transformation that occurs? Making an alkyl halide into an alcohol, an alcohol into a carboxylic acid, a carboxylic acid into an ester. There's usually some specific set of reagents that reproducibly causes that reaction as long as you're using the same functional group. Sometimes, there are special reaction conditions: some reactions won't work at all if they're exposed to water, or to oxygen, or they can only be performed successfully at really low temperatures. If we know the mechanism of the reaction, then we know something about what's going to happen to the stereochemistry of the reaction, and we'll know something about the regiochemistry that's going to result from these reaction. We're going to be able to use kinetics, thermodynamics, equilibrium, to make some statements about how mechanism will affect stereochemistry and regiochemistry. These six items, then, are what you're going to be worried about for each reaction that you learn.

[road map for the quarter][flash cards]

[lab reports]

$pK_a \equiv -\log_{10}K_a$; $pK_a \gg 1$

weak acid \rightarrow low dissociation $\rightarrow K < 1 \rightarrow pK_a \gg 0$

Acetic acid, being a weak acid ($pK_a = 4.76$) would only want to dissociate to a small degree (~1%). Since NaOH is a strong base, it can force acetic acid to become neutralized (to dissociate).

If acetic acid is forced to dissociate:

- 1) There are only products, no reactants, so $Q \gg K$
- 2) Only the reverse rxn for the dissociation of acetic acid is possible (no reactants).
- 3) The system is driven to a higher potential energy.

Since the equilibrium for acetic acid has been forced too far towards products, acetate will react with water to re-form acetic acid and re-establish equilibrium. \therefore neutralized \neq neutral

s-character \rightarrow % of s orbital in a hybrid

In polyelectronic systems, s orbitals are lower in energy than p orbitals. Hybrids with greater % of s-orbital (greater s-character) are therefore lower in energy, so electrons in an sp orbital are lower in energy than sp^3 .

Structural effects that stabilize a product make it easier for the product to form, which in this case means the original acid dissociates more easily \rightarrow lower pK_a

Inductive effect – Since oxygen is electronegative, it can pull electron density away from hydrogen, making the hydrogen dissociate more easily, making ethanol more acidic

Resonance effect – If the negative charge formed by dissociation can be delocalized, it is effectively easier to form the anion, meaning the parent acid is more acidic.

1) synthetic utility (transformation); 2) reagents; 3) conditions; 4) mechanism; 5) stereochemistry; 6) regiochemistry

Structures (remaining structures identical to lecture 17A)

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