

Interpretative Spectroscopy
Prof. Maravanji S. Balakrishna
Department of Chemistry
Indian Institute of Technology Bombay

Lecture 09
Introduction to ^{13}C NMR Spectroscopy

Hello everyone, once again I welcome you all to MSB lecture series on Interpretative Spectroscopy. This is the ninth lecture in the series. In my previous lecture, I was discussing about the second order coupling. Second order coupling we come across more often with 1-hydrogen (^1H) NMR because of small chemical shift range, it is 1 to 10. As a result, what happens, especially, when we have chemically equivalent and magnetically non-equivalent protons present on the same carbon atom, that is, geminal coupling arises. Whenever geminal coupling arises, we come across second order splitting and also when we have two methylene groups on either side when they are substituted in a different way, we come across again difference in magnetic properties of hydrogen atoms present on the same carbon atom.

As a result, we come across second order splitting. So, let me continue from where I had stopped. So, this is the spectrum of styrene recorded at 60 megahertz (MHz). You can see the peaks are little different compared to what we see when the same spectrum is recorded higher field.

So, here you can see some sort of pyramidal effect. Pyramidal effect means when you see multiplet of different lines, if they are in the pyramidal shape increasing intensity on both sides resulting in some sort of tower type. That will give a hint that this is not a simple first order spectrum, this is a second order spectrum. One such example is shown here in case of styrene (C_8H_8), olefinic region, I am referring to. If you just see the interaction of HA is not same with interaction of HB and as well as HC. As a result, we

come across one is cis coupling, one is trans coupling and also the coupling between B and C.

So, here it is a typically ABC type spin system and the advantage with higher field is the chemical shifts move further away. If you increase the magnetic field as a result complicated second order spectrum would become simplified first order spectrum. There is the advantage of recording NMR at much higher field. So, in this one the peaks are pyramidal in shape can be seen in all ABC and ABX spectra. Olefinic region of mono substituted alkenes, exhibit often ABC or ABX spin system, with peaks having pyramidal shape, but spectra taken at higher field strength resemble AMX spin system.

Also in my earlier lecture, I showed you how ABC become ABX and eventually it becomes AMX spin system in the case of styrene (C_8H_8) itself. For example, you can see here, this is recorded at much higher field. Just focus your attention to this olefinic region. All are having very clean doublet of doublet (dd) pattern, because of coupling with different protons in a different way with different magnitude of coupling. For example, if you consider HA and HB this the higher coupling and first that will show a doublet (d) and then this will be coupled with cis one and to see doublet of doublet (dd) and correspondingly HB and HC also show in the same fashion. So, this is for HB and this is for HC.

You can see here the values presented 5.76, 5.25 and 6.72. You can see clearly 6.72 corresponds to this one, where we will see this trans coupling. First doublet and then it is further split by cis coupling to give another doublet. So, it appears as a doublet of doublet (dd) in the same fashion. This one is at 5.76. This will show first coupling with this one and then it will couple with this one, this magnitude is very small. That is the reason, you can see the space between the two lines is much smaller, whereas this one is due to this coupling. It first appears as a doublet and then it further appears like a doublet of doublets and if you see the coupling, whether you measure from the chemical shift of this one to this one or this one to this one, that should be identical. And similar spectrum is also shown here, recorded at 90 megahertz (90 MHz).

Again, you can see pyramidal. The effect clearly shows that it is also an ABC spin system, but if you record this one at 400 megahertz (400 MHz) it can be further simplified to appear as AMX spin system like what I showed in my previous slide. Now, I have another interesting molecule here, in this one, you can see again HA, HB and HC. This is a typical ABC spin system. You can see I have three figures listed here. The figure one is simulated first order spectrum. This second one is simulated spectrum with different coupling values are given. J_{AB} equal to 18 ($J_{AB} = 18$ Hz) and J_{AC} equal to 2 hertz ($J_{AC} = 2$ Hz) and J_{BC} equal to 10 Hertz ($J_{BC} = 10$ Hz), and then actual ABC portion of this molecule is shown here. This is pretty second order, but when you take it to higher field it appears like a simple AMX spin system showing doublet of doublets (dd) in each case here. And of course, here you can see again pyramidal effect is there, and it is much simplified. When you go for higher field, that means the figure one is simulated first order spectrum, whereas figure two is simulated second order ABC spectrum and figure three is the actual spectrum. So, among different types of second order spin systems we come across, that is A_2X_2 , A_2B_2 , $AA'XX'$ or $AA'BB'$ or A_2X_2 .

So, among all those things A_2X_2 is the least common spin system and one such system is that of difluoromethane (CF_2H_2) and each hydrogen is coupled equally to each fluorine and hence it is A_2X_2 . In case of difluoromethane (CF_2H_2) it is a typical example for A_2X_2 spin system or coupling system. And one should remember is, if we have a molecule having two methylene groups (CH_2) adjacent to each other in the middle and substitutes with similar electronegativity at both the ends, that means here as well as here, if you have groups with similar electronegativity that would show A_2B_2 spin system, one should remember that. Now, let us try to understand few terms so that understanding their features would become rather easy. Diastereotopic protons in organic chemistry, you must have studied, but nevertheless let us refresh our knowledge and understanding about these typical terms. Diastereotopic protons occur if a chirality center is present in the molecule. If you see here, this already a chiral center in the molecule. Diastereotopic protons are chemically non-equivalent and hence they show different chemical shifts, I am referring to H_A and H_B and replacing them results in compounds which are diastereomers. If you replace them with something else then that results in diastereomers.

And what are isotopomers? Isotopomers have the same number of atoms of each isotope, but in a different arrangement. Isotopomers are isotopic isomers which differ by isotopic substitution. For example, if you take CH_3OD , here H is replaced by D and if you compare this one with CH_2DOH , the number of hydrogen and deuterium remains the same here, but the substitution is at a different place. Again, you can see here, D comes here and we have this one among these these; are all called isotopomers.

And what are diastereomers? Diastereomers are the stereoisomers that are non-identical and do not have mirror images. As a result, they are non-superimposable on each other. If you do not have identical mirror images then they are non-superimposable on each other and such isomers are called diastereomers. For example, you can see here, this portion, if you compare this is non-superimposable mirror image, but on the other hand if you consider this portion here that is not.

So, these two are called as diastereomers and what are enantiomers? A pair of molecules existing in two forms that are non-superimposable mirror images that are enantiomers. So, now let us look into a typical AA'BB' spin system as I mentioned we give the terms AA prime BB prime (AA'BB'), when A and A' are magnetically non-equivalent, but are chemically equivalent. Similarly, BB prime (BB') is given here which are chemically equivalent, but are not magnetically. So, this is A and this is A prime (A'), this is B and this is B prime (B') and although same J values were used while simulating, for ortho, meta and para chemical shift difference was reduced to 40 hertz (40 Hz). They are quite different structures as well. One is para and the other one is ortho. For example, if you see here, simulated AA prime BB prime spectrum for this molecule. here in all cases, the coupling constants are taken as 9 hertz, 3 hertz and 1 hertz, respectively ($J_{\text{HH}} = 9, 3, 1\text{Hz}$), and here delta A is 630 ($\delta\text{A}=630\text{ Hz}$) and delta B 700 hertz ($\delta\text{B}=700\text{ Hz}$), whereas in this case delta A equal to 630 ($\delta\text{A}=630\text{ Hz}$) and 700 hertz ($\delta\text{B}=700\text{ Hz}$), but you can see the pattern is a very different and again you can see this pyramidal effect; can be seen here. So, this shows that AA prime BB prime (AA'BB') spin system and another example is there, and here again, these two look identical, yes, they are identical, but they are chemically equivalent, but not magnetically.

So, as a result using AA prime (AA') and BB prime (BB') the moment you see this kind of prime, prime indicates that both of them are chemically equivalent, but they are not magnetically. So, in this case what we get is AA prime BB prime (AA'BB') spin system. This is another example, bromo anisole. The reason is, if you consider the coupling of this one, with this one is different from coupling of this one with this one and similarly the coupling of this one is different from coupling of this one. Because they are the bonds. If you consider they are farther away as a result, although they are chemically equivalent. Their interactions are different and hence that results in a different spin system, second order spin system, that we call here as AA prime BB prime (AA'BB'). Another example here for para-bromo chlorobenzene (*p*-BrC₆H₄Cl). Now let us look into hydrogen and carbon chemical shifts for better understanding. I have given here for comparison, for the same functional groups: both 13-carbon (¹³C) and 1-hydrogen (¹H). Chemical shift ranges I have given here. If you just see here, aldehyde group and carbonyl group, it comes around 9 to 10 in case of ¹H NMR, whereas in case of ¹³C, it comes around 200 ppm. Similarly if you take ortho hydrogen, where ortho has halogen, it comes around 7 to 8, and it comes somewhere here, and then if you take olefinic hydrogen, that comes between 6 to 5, whereas here, it comes between 100 to 150, where it is aromatic carbon as well as olefinic carbon, and then if you see a carbon having hydrogen as well as halogen or oxygen, it comes between 3 to 4 ppm, whereas in this case it comes around 50 to 90 ppm, and similarly, if you see a carbonyl group adjacent to another carbon having H, it comes around 2 ppm, whereas here we will see that one around 50 ppm. Similarly, alkanes would come around 0 to 30 ppm in case of ¹³C NMR. So, let us look into the general information about ¹³C NMR. In ¹³C NMR, we have to consider carbon has two isotopes 12-carbon and ¹³C with non-zero nuclear spin. In case of ¹²C, it has no magnetic spin thus I value is 0 (I=0) that constitute about 99 percent and remaining 1 percent is ¹³C that has magnetic spin of half (I=1/2) but is only 1.1 percent of carbon in a given sample.

So, the gyromagnetic ratio of 13-carbon (¹³C) is one fourth of that of hydrogen, the signals are very weak, difficult to identify as they often get lost in noise, if enough quantity of sample is not taken. Then especially quaternary carbons will be merged with

noise, as a result we may not be able to see such signals, that means we have to take more sample and hundreds of spectra are taken average to get a single refined spectrum. I have shown here ^{13}C and ^1H NMR spectra of 1H-pyrrole-2-carbaldehyde ($\text{C}_5\text{H}_5\text{NO}$), and you can see here, the aldehyde proton comes around 9.4 ppm, whereas in case of ^{13}C , it comes around 180 ppm and these two are assigned. You can see here: for CH and CH and CH, these three protons and then corresponding ones are shown here, and then if you look into the sample recorded in CDCl_3 in case of ^{13}C , what we are getting is a triplet (t) of equal intensity. So why that happens because if you just look into CDCl_3 here, for D, $I = 1$. If you just use this formula to identify how many peaks will be there, so 2 into 1 into 1 into 1 so it gives 3 ($2nI+1 = 2 \times 1 \times 1 = 3$). So here I equal to 1 the intensity will be 1 is to 1 is to 1 (1:1:1), as a result in case of ^{13}C NMR of CDCl_3 shows a triplet (t) of equal intensity. I have given another example here, you can see the same example I discussed in the previous slide and the corresponding chemical shifts are given here and if you just see here 1, 2, 3 so all are different. Here you can see all carbon signals are shown here, and for example, it is 127.1, 111.7, 121.6, 132.4 and then 182.6. So, all signals are shown here. You can see the distinct chemical shifts for each carbon atom, if they are chemically and magnetically non-equivalent and if you just look into ^1H NMR spectrum you can see a typical spectrum shown here. So, what are the differences between ^1H and ^{13}C techniques, when you are running NMR. Resonance frequency is one fourth of ^1H frequency, since gyromagnetic ratio is one fourth and gyromagnetic ratio is directly proportional to Larmor frequency, as a result it is very easy to calculate by just looking into the ratio of gyromagnetic ratio of two individual nucleus with respect to hydrogen. For example, if you take 60 megahertz (60 MHz) ^1H NMR, the corresponding magnetic field strength will be 15.1 megahertz (15.1 MHz) for carbon-13 (^{13}C).

So, unlike ^1H NMR peak areas are not proportional to the number of carbons here. Carbon atoms with more hydrogen atoms absorb strongly and if carbon do not have hydrogen atoms, then absorption is very weak. As a result, it is very difficult to identify such samples especially, the noise ratio is very high, that is the reason, we have to take larger amount of sample to get to identify those quaternary carbon atoms or carbon atoms without having hydrogen atoms directly attached to it. So now let us look into spin-spin splitting. So, it is unlikely that a ^{13}C signal would be adjacent to another ^{13}C . So, splitting

by carbon is negligible, that mean carbon-carbon splitting is not seen unless it is enriched with ^{13}C isotope because, what happens, if we have two neighboring carbon atoms and it is highly unlikely that in a given set of molecules, both of them will be ^{13}C - ^{13}C . It is almost like taking two bottles with 100 marbles, 99 of one color and one of another color, and then if you mix it, on shaking you will come to know how many times these two colored ones come together. So, if you look into the probability that probability is very very low as a result we do not observe ^{13}C - ^{13}C coupling in a normal molecule, where it is not enriched. Of course, if you can enrich and record then we can see ^{13}C - ^{13}C coupling. ^{13}C will magnetically couple with attached protons, and adjacent protons, however, if carbon is attached to hydrogen or other NMR active nucleus, such as fluorine or phosphorus, you can see coupling between them. These complex splitting patterns are difficult to interpret. If we take an organic molecule, we have numerous hydrogen atoms are there and if we see C-H coupling with two bonds coupling three bond coupling and other things the ^{13}C NMR spectrum would look very complicated and then assignment of signals would become very difficult as a result what we do is the decoupling. So, proton spin decoupling is to simplify the spectrum. Protons are continuously irradiated with noise so they are rapidly flipping that means we are not giving enough time for protons to interact the way they were in the molecule because of continuously irradiating them with the Larmor frequency corresponding to those hydrogen atoms.

The carbon nuclei see an average of all possible protons spin states as a result, it does not couple with any of them. Thus, each different kind of carbon gives a single unsplit peak and this we call as proton decoupling, often we show in this fashion. If ^1H is written in flower bracket, next to ^{13}C or anything. This means it is ^1H decoupled ^{13}C NMR spectrum ($^{13}\text{C}\{^1\text{H}\}$ NMR). So, half resonance decoupling. So ^{13}C nuclei are split only by the protons attached directly to them or by any other NMR active nuclei such as ^{31}P or ^{19}F , the n plus 1 (N+1) rule applies here. You can also use $2nI$ plus 1 peak ($2nI+1$), if you want to add the spin nuclear value I then interpretation of ^{13}C NMR spectra. So, the number of different signals indicate, the number of different kinds of carbon. That way it is very simple and when you decouple, it becomes even more simplified. The location indicates the type of functional group as we have a distinct chemical shift for each

functional group, it is very easy to identify, what kind of functional groups we have in a molecule by simply looking into the chemical shifts. The peak area indicates the number of carbon atoms. If integrated normally we do not see the splitting pattern of off resonance decoupled spectrum, indicates the number of protons attached to the carbon. The splitting pattern of off-resonance decoupled spectrum indicates the number of protons attached to the carbon. Now, we will look into ^{13}C NMR spectra taken with and without proton coupling. For example, for this butane or this ketone ^{13}C NMR is recorded both with coupling without coupling. Without coupling, you can see we have 1, 2, 3, 4 different carbon atoms. In the coupled one, you can see this methyl group (CH_3) is coupled with 3 protons (3 H) as a result, it will be a quartet (q). We can see here and then this methylene (CH_2) is coupled to 2 and we get a triplet (t) here and then again this is coupled to 3 hydrogen atoms again a quartet (q) here and this one has no directly attached hydrogen, as a result it shows one singlet (s) here.

This of course, little less complicated. So, we can take coupled one, there is no harm, but when we have a complex molecule, a protein molecule or bio-molecules, then it is advisable to record decoupled spectrum for understanding and elucidation of the structure. So, let me continue in my next lecture. Thank you very much. Thank you.