One and Two Dimensional NMR Spectroscopy for Chemists

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Lecture – 11
External and Internal Interactions in NMR

Welcome back, in the last couple of classes, we discussed quite a bit about fundamentals of spin physics and the basic important parameters concerning the spin physics to understand, viz., what happens the nuclear spins in a magnetic field. We understood spin angular momentum, spin quantum number, magnetic quantum number, magnetic moment, interaction of the magnetic moment with the external magnetic field. What happened to the magnetization when we apply radio frequency pulse, how to detect the signal various aspects we discussed.

Now, we have to proceed further. Here afterwards we will start interpreting the NMR spectrum for which we need to understand some of the important parameters. We start with chemical shifts today.

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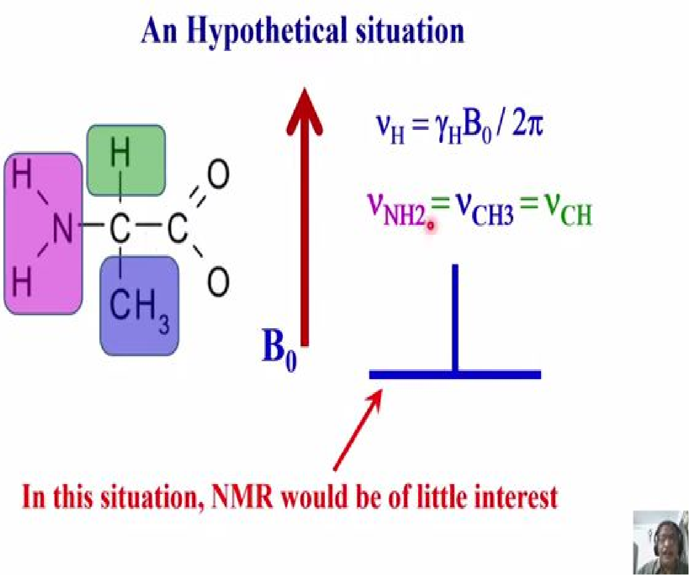

An Hypothetical situation

$$\nu_H = \gamma_H B_0 / 2\pi$$

$$\nu_{NH2} = \nu_{CH3} = \nu_{CH}$$

In this situation, NMR would be of little interest

Let us consider an hypothetical situation, a hypothetical situation like this; A molecule has NH2 protons, CH proton and CH3 protons. Remember, I told you in the last class, again I am repeating, in the NMR jargon if there is hydrogen, if you say a proton, it refers to hydrogen. So if I say NH2 protons, that means I am talking about these 2 hydrogen atoms. So there are 3 different functional groups present in this molecule.

Now, place this molecule in a magnetic field, you want to see the NMR of this. Recall my basic condition, which I discussed for the resonance condition in NMR; this was given by ν = gamma into B0 over 2 pi. Of course, now I am talking about the protons here, I simply plug it as the resonating frequency of the proton, gamma is a gyromagnetic ratio for the proton, B0 is the magnetic field, and of course 2 pi. In this molecule, of course, you can also study nitrogen 15 NMR, nitrogen 14, carbon 13, O17 NMR. Various NMR active nuclei are present in this molecule.

But for the discussion to continue, I am concentrating on only protons. Hence, my basic resonance condition, I have written like this ν_H = gammaH into B0 over 2pi. Now, if you proceed further in this molecule according to this equation do you find any distinction between different protons present here? This is a general equation, it does not say the resonatic condition, whether it is for a NH protons or CH proton or CH3 protons. This equation does not distinguish any of these functional groups.

Then what does it mean? According to this equation, if I go by this, the resonatic frequency for NH2 protons, CH proton, and CH3 protons, all the 3 are same. That means there is no distinction between any functional groups, as for this basic equation. Then what I am going to get? If I take the NMR spectrum, I must get a single peak for this molecule, single resonance frequency for protons. I took the simple example of a small molecule.

Of course you can take any molecule of your interest, it could be even a very big protein molecule, any big bio macro-molecule, does not matter. Now, as far as this equation is concerned with our basic understanding, whatever the molecule take, there may be any number of functional groups present here, any number of protons present in that molecule, I must get only a single peak for proton NMR. If that is the case NMR would be of very little interest for us, because the interest of the NMR is not just observing one single peak for any given molecule,

Then remember I said NMR ubiquitous technique, which is used in various branches of science, this NMR utility would not have been there, and interest would have die down a long time ago.

So, the question comes, what makes NMR a very powerful technique? Let us answer this question now.

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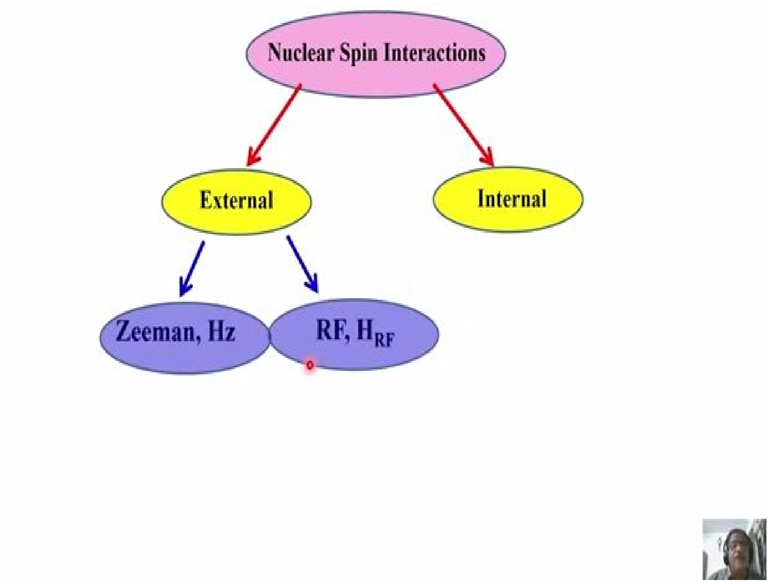

Nuclear Spin Interactions

External

Internal

Zeeman, Hz

RF, H_{RF}

For this we need to consider few nuclear spin interactions. What are the nuclear spin interactions? I could broadly classify them into 2 types of interactions; one is external interaction, other is internal interaction. Now the question is what is an external interaction? Of course we all know this; I have been discussing this, since last several classes. First external interaction is you must remember, I said moment you put the magnetic moment that the nuclear spin in a magnetic field, there is an interaction of this nuclear magnetic moment with the external magnetic field. You please remember my basic equation I wrote; E = – μ dot B0, where the magnetic moment was interacting with the magnetic field, this is an external magnetic field. As I said NMR spectroscopy requires the huge external magnetic field and this was the first and foremost external interaction, which we have already discussed, which we also called as the Zeeman Effect. This is the Zeeman interaction.

Second, you remember you put the sample in a magnetic field, the spin get aligned. That is fine, that is the first external interaction and we understood what is magnetization everything, bulk magnetization. But we also discuss for the detection of the signal we have to perturb this. We have to create a non-equilibrium situation where the bulk magnetization will be in thermal equilibrium, so, it is static.

I said, we apply radio frequency signal in a direction perpendicular to the static magnetization and we tilted the magnetization. Assume z - axis, which is a direction of the magnetic field, to the XY plane, either X axis or Y axis, depending upon the pulse we apply. What is this interaction? It is the interaction of the radio frequency with the nuclear spins. What is the after all a radio frequency? It is nothing but an electromagnetic wave. The radio frequency signal which we are applying, radio frequency pulse I am sending, it is nothing but a electromagnetic radiation which has electric component and magnetic component. Now, the magnetic component of this is also interacting with the nuclear spin. It is like bringing 2 magnets together. There will be an interaction. So, this we are sending the radio frequency signal from outside, hence I call this external interaction.

So, these are the external interactions that is Zeeman interaction and interaction of the radio frequency of the nuclear spins, we discussed in couple of previous classes.

In addition to this, there are other type of interactions, which are internal. Internal, I mean within the molecules. You take any molecule of your interest within the molecule, there are several other internal interactions; these internal interactions also we have to understand. So, far we have not discussed any of them, then the question is what are these internal interactions?

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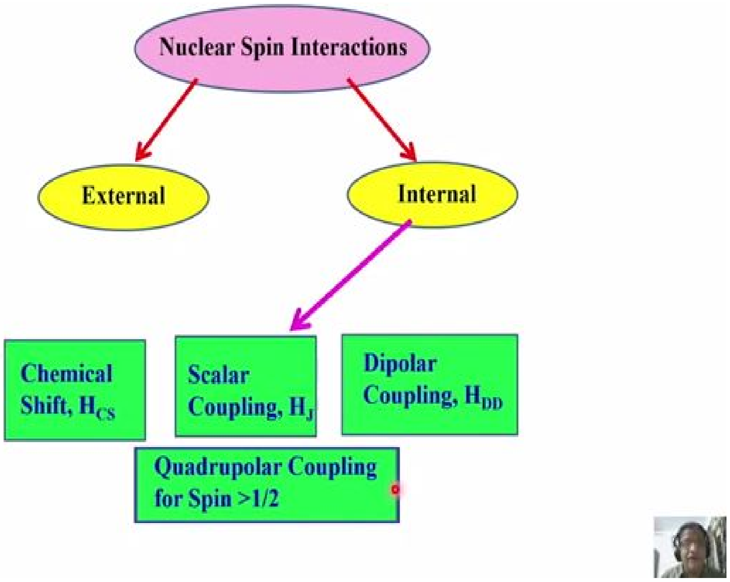

Nuclear Spin Interactions

External

Internal

Chemical Shift, H_{CS}

Scalar Coupling, H_J

Dipolar Coupling, H_{DD}

Quadrupolar Coupling for Spin >1/2

This again, I have written 4 types of interactions, one is the chemical shift; most important interaction. We will go and understand all these things in detail. Today in fact, especially we discuss a lot about chemical shift. This comes because of chemical environment, electronic charge distribution at the site of a given nucleus, that is one type of internal interaction. Second, this scalar coupling, also called J coupling.

What is this? Remember, when we have a molecule, we have chemical bonds. Consider a molecule, let us say, I have a CH proton here, I have another CH2 proton in between, there is one chemical bond, there are some other substitutions outside, let us not worry. The proton of this CH can interact with the proton of this CH2. These 2 protons and this proton can interact, because this nuclear spin we can take a tiny magnet, this nuclear spin we can take a tiny magnet and these 2 can interact, where the medium of interaction or the magnetization transfer is through covalent bond. So, this scalar interaction, scalar coupling, also called J coupling is because of covalent bond. Covalent bond mediated interaction between 2 nuclear spins. Please remember this. This is again internal the molecule.

We can also think of another type of interaction, called dipolar coupling. What is this dipolar coupling? For this scalar interaction we require chemical bond. Think of a situation, there is no chemical bond, a big molecule is there which in a 3 dimensional conformation, there are 2 protons which may be separated by several bonds away, does not matter, but when you see them spatially, they may come close to each other, very close within 2 or 3 angstroms away, or 3 or 4 angstroms, let us say, that come close in space.

But then remember, again 2 magnets coming close in space, there can be direct interaction without invoking chemical bond. This is spatial interaction, interactions between 2 nuclear spins or 2 magnets, through space. And you can understand because it is a through space interaction, the spatial proximity is very important. When you bring these spins closer and closer and closer, the interaction becomes stronger and stronger. As you go far away the interaction reduces.

It is distant dependent interaction, because this interaction is taking place through space. Just imagine 2 magnets are there, you keep one magnet far away, other magnet far away. There will be an interaction, as you bring closer and closer and closer and you come very close, you have seen it, you know would have seen in your school days or early college days, the 2 magnets when they come close, there is an interaction, either attraction or repulsion depending upon the way you bring it closer. This is another type of interaction between the nuclear spins through space called dipolar interaction. And this is orientation dependent; remember this depends upon the orientation. We will discuss more when you go to coupling interactions. All these 3 parameters pertain to spin half nuclei. Now I am talking about spin half nuclei, but you can consider nuclei whose spin is greater than half. For example, we understood nitrogen 14 which has a spin 1, we calculated that, in one of the classes. Take deuterium, it is spin is 1, and such nuclei, I told you, are quadrupolar nuclei.

And that type of nuclei whose spin is 1 or greater than half, can have an internal interaction, which is called as quadrupolar coupling. Remember, I have mentioned 4 different types of internal interactions these 3 corresponds to, or pertains to the spin half nuclei. And this is for spin greater than half. Of course all the interactions will be present for these. Not that for the spin greater than half, these 3 are absent. No everything will be present. Only for spin half nuclei, this is absent. Please remember that point.

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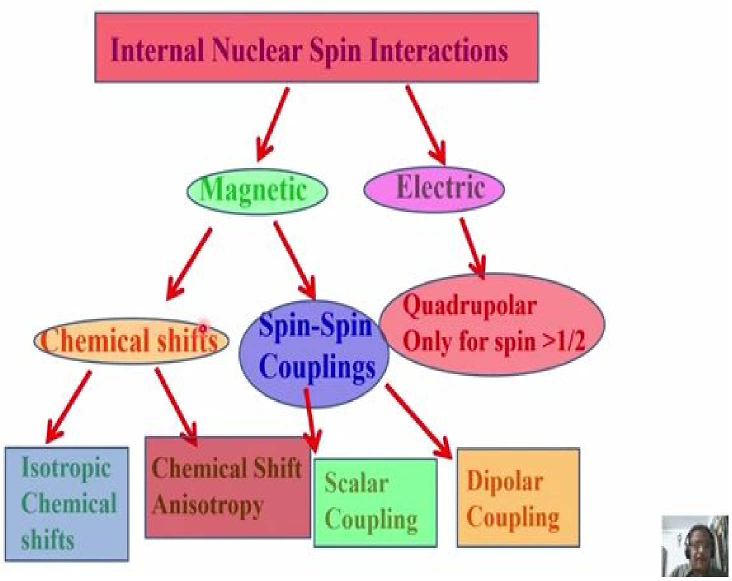

Internal Nuclear Spin Interactions

Magnetic

Electric

Chemical shifts

Spin-Spin Couplings

Quadrupolar Only for spin >1/2

Isotropic Chemical shifts

Chemical Shift Anisotropy

Scalar Coupling

Dipolar Coupling

Now, these internal nuclear spin interactions, again I can classify into 2 types. One type of interaction is called magnetic interaction, other type of interaction is called electric interaction. What are these electrical and magnetic interactions? These magnetic interactions can be further classified as chemical shifts and spin-spin couplings. The electric interactions are for those nuclei who spin is greater than half, that is a quadrupolar interaction.

Please remember, in the previous slide, I said 4 different types of internal interactions; out of this the quadrupolar coupling is coming because of the nuclear spin which is greater than half; is an electric interaction. This is the only electric interaction, all other remaining 3 interactions which I mentioned, the internal interactions are magnetic interactions. Now, if I go further, this internal interaction, the magnetic interaction, like for example, chemical shifts can further divided into 2 types. One is isotropic chemical shift and the other is chemical shift anisotropy. That means, the chemical shift has 2 parts, one is an isotropic part and other is an anisotropic part, you understand. Remember all the parameters in NMR can be expressed as tensors, we can define them as tensors, a 3 by 3 matrix having 9 elements. we can define them, and all these parameters are anisotropic in nature.

That means, the value of this parameter when measured in different directions will be different. It is not the same in all directions, that is what happens. All parameters in NMR, for example, chemical shift has isotropic component and anisotropic component. I will tell you why I should anisotropic component comes later, and then similarly, spin-spin coupling they can be further classified into scalar coupling and dipolar coupling.

I already told you the scalar coupling is one which mediates through covalent bond, whereas dipolar coupling is through space interaction. That is what I said. strictly, if you start going analyzing further, this scalar coupling also has an isotropic part and an anisotropic part. The isotropic J coupling and also J anisotropy is there. I am not classifying further, it will become too complicated for you at this stage; you do not have to worry.

Similarly, the dipolar coupling is also there, that again we can divide into 2 parts, we will not go into more details. First remember, broad classification is chemical shift has isotropic part and anisotropic part. Similarly spin-spin couplings, I have classified as scalar coupling and dipolar coupling.

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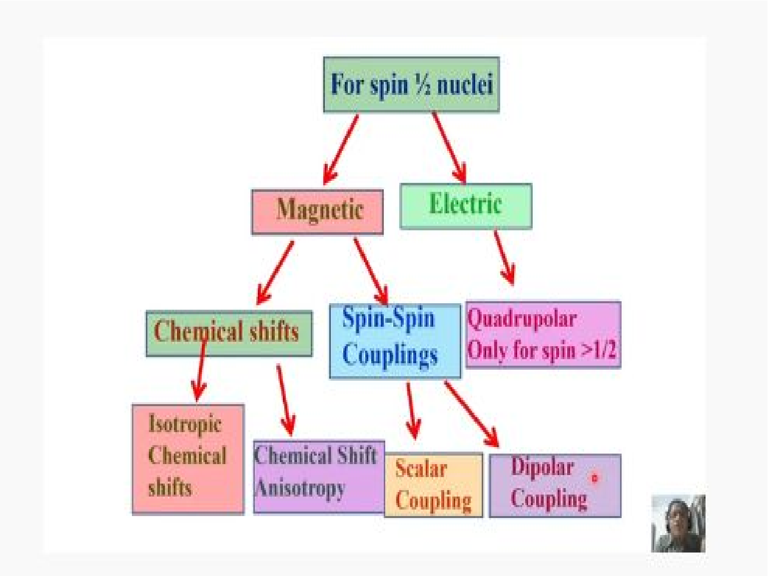

For spin ½ nuclei

Magnetic

Electric

Chemical shifts

Spin-Spin Couplings

Quadrupolar Only for spin >1/2

Isotropic Chemical shifts

Chemical Shift Anisotropy

Scalar Coupling

Dipolar Coupling

Now, I concentrate on spin half nuclei, basically in this course, we always concentrate on spin half nuclei. We do not go to spin 1 nuclei. Only, in special examples to understand the coupling of spin half nuclei with spin 1 nuclei, I take some examples while interpreting the spectrum, later. But at the moment, for most of our discussion, we concentrate only on spin half nuclei. When the spin half nuclei, what did I say? This electric component coming due electric interaction, coming because of the quadrupolar coupling must be 0, it should not exist. True that will disappear. So, for spin half nuclei, the electric interaction is 0. We have only magnetic interaction, which already been classified as 2 parts, chemical shifts and spin-spin couplings. Again I showed you previously, we have isotropic and anisotropic parts of chemical shifts, spin-spin coupling, scalar coupling and dipolar coupling.

So, this again I told you we have isotropic and anisotropic parts, all those things we can discuss. But, again depending upon the state in which we study the NMR, state of the molecule, whether it is a solution state or whether in the solid state. What happens if you put the molecule in a solution? Let us say I take some water soluble molecule, I take in water and dissolve. Completely dissolves at any given instant of time.

Let us say there will be a thermal agitation going on, rapid tumbling motion of the molecules. There is some sort of motional averaging, what happens in that case? Certain parameters disappear, what are these parameters which disappear.

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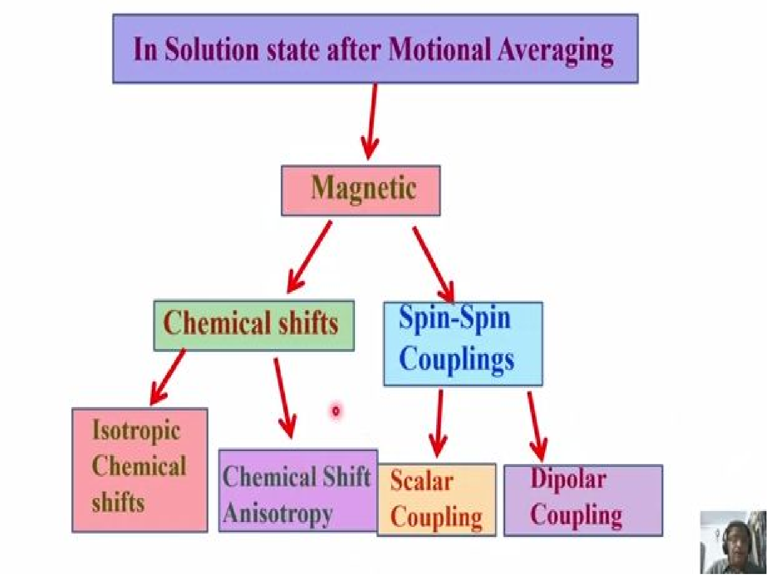

In Solution state after Motional Averaging

Magnetic

Chemical shifts

Spin-Spin Couplings

Isotropic Chemical shifts

Chemical Shift Anisotropy

Scalar Coupling

Dipolar Coupling

See, when I go to the solution state when I take into account the motional averaging, the anisotropic part will disappear; because, I told you the anisotropy means you measure the value in different directions will be different. And there is a rapid tumbling motion going on with the averaging of the motion takes place all as anisotropic part goes to 0. You will not see this effect in the NMR spectrum in the solution state.

What about the dipolar coupling? The dipolar coupling as I told you, depends upon the direction of orientation of internuclear vector. it is orientation dependent, that means, when there is a motional average, all possible orientations present; that means when I take average, this dipolar coupling also goes to 0. Understand, in this solution state the anisotropy part of these interactions goes to 0. Similarly, scalar coupling anisotropy also goes to 0, dipolar coupling goes to 0, chemical shift anisotropy also goes to 0.

Then, what are we left behind? We are left behind only 2 things. isotropic part of the chemical shift and scalar coupling, that is J coupling. Remember when I go further, when we discuss scalar couplings, I will tell you all those things. The very fact it is a scalar, the word it is saying, it is not orientation dependent. That is the reason why this through space, I am sorry, through covalent bond mediated interaction, the scalar coupling which is mediated through covalent bond is not going to be averaged out in solution state.

This motion averaging has no effect on the scalar coupling, that is covalent bond mediated coupling, that is why it is called scalar coupling, we will talk about it later. So, these are the 2 parameters which we are left behind. Again, when I go to the solid state NMR, may be in the last, 1 or 2 classes I will briefly give you an idea, because it is not the aim of this course to give in depth information about solid state NMR. I will touch upon some of the principles and applications where you try to use them in that solid state, where there is no motional averaging, all these interactions are present. Now in the solution state, we will talk about only these 2 parameters.

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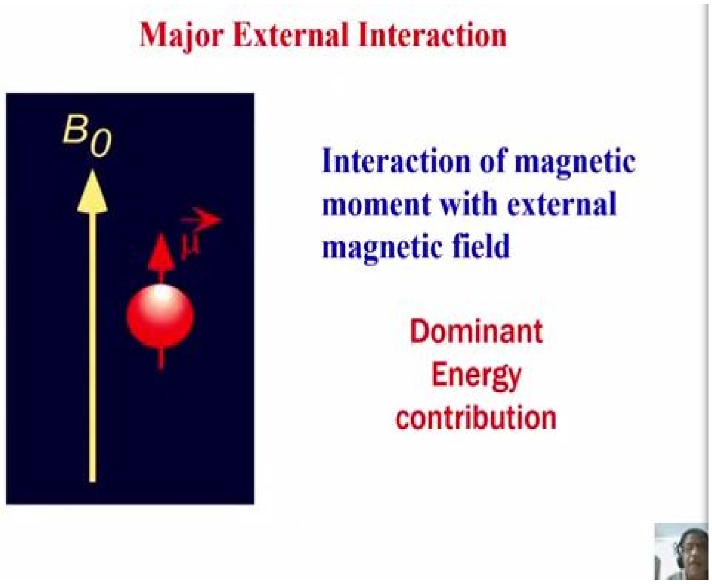

Major External Interaction

Interaction of magnetic moment with external magnetic field

Dominant Energy contribution

With this information, with the discussion that we had, we will start looking pictorially about various types of interactions and their strengths. I said external interaction, there are 2 types. The internal interactions, there are 4 different types I have explained. Now, you may ask me a question, which has a more interaction strength. between the 2 external which is more? And among the 4 internal interactions which is stronger, which is dominant interaction and between external internal which is dominant? these questions can be asked.

First, we will understand the external interaction, the major interaction is what? It is interaction of the magnetic moment here with the external magnetic field, the strong magnetic field we are going to put, this is the magnetic moment, the spin of the nucleus, and it interacts with B0 magnetic field. Why I say it is dominant interaction, and interaction strength is very large. This is a major interaction, you remember, we calculated the energy, you know in one of the previous classes we even calculated the frequency.

This will be of the order of several megahertz, the separation energy is so much, when we calculated the frequency, it is of the order of few 100s of megahertz. Then what about other interaction, the radio frequency interaction is very small. Among the 2 external interactions, this interaction is dominant. it is fine.

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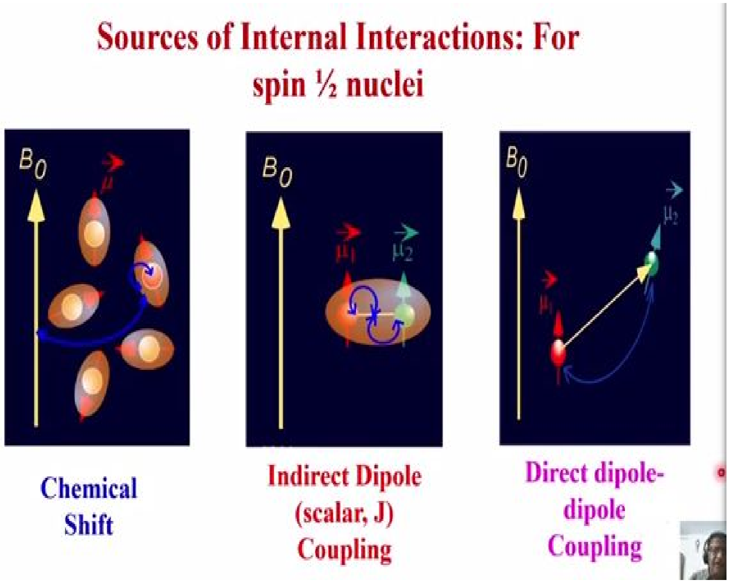

Sources of Internal Interactions: For spin ½ nuclei

Chemical Shift

Indirect Dipole (scalar, J) Coupling

Direct dipole-dipole Coupling

Now, let us look at the sources of internal interaction for spin half nuclei, and which is dominant we will come to that later. First chemical shift as I said this chemical shift is arising because the nuclear spins are not bare spins; they are not simply bare spins sitting. The nucleus is surrounded by electrons. The electron, mind you, I told you, it has a spin. You can take it as a tiny magnet, again there is an interaction going on.

As a consequence of the charge distribution at the site of the nucleus, there is some interaction, that causes some effect of the NMR spectrum. That is what we are going to understand today, is called chemical shift, and of course between 2 magnetic moments, that is between two nuclear spins remember, I told you in earlier class, nuclear spins, magnetic moments and all those things. These are all jargons we keep changing while using, but everything is same. if I say 2 magnetic moments, fine, if I say interaction to nuclear spins, fine, There is no difference between these 2.

This through covalent bond can take place I told you, this is called indirect coupling or scalar coupling, also called J coupling; and the next one is the dipolar coupling, which I said is a through space interaction.   I say between these 2 spins, there is a covalent bond here. Here there is no covalent bond between this and this, the interaction is going through space, this is through space interactions. this is called dipolar coupling, nuclear spin is a dipole, if you consider spin half nuclei.

Remember I told you it is a dipole, for spin half nuclei this is a dipole and this dipole-dipole interaction is there, this is directly taking place and is called direct dipole coupling, dipole-dipole coupling, also called dipolar coupling. This is given by the DIJ, this is J, JIJ a scalar coupling into space I and J is JIJ. This is the dipolar coupling between 2 spins through space, is called the DIJ. You call you can use different notation but colloquially most commonly DIJ is the direct coupling is referred to.

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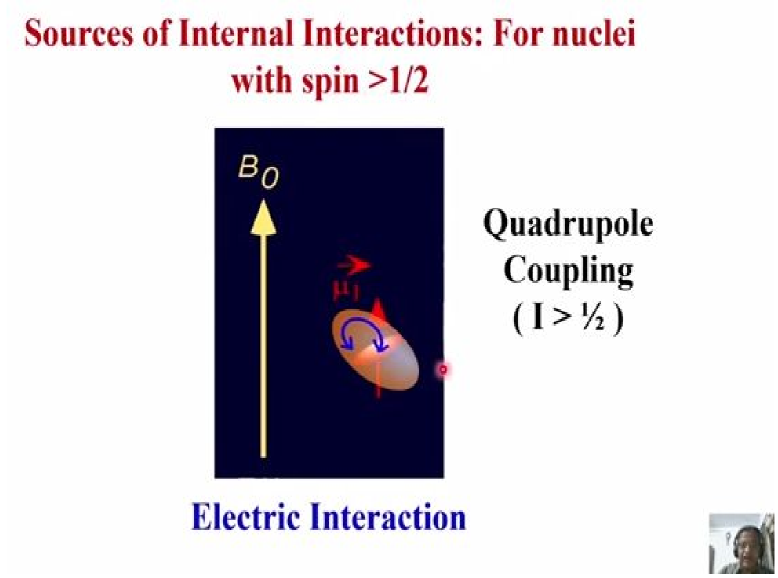

Sources of Internal Interactions: For nuclei with spin >1/2

Quadrupole Coupling
(I > ½)

Electric Interaction

Of course next one I said is greater than half is the electric interaction. if we have quadrupolar polar spin, that we are not any way discussing; this is an electric interaction when the nuclei have spin greater than half, this is also dominant contraction.

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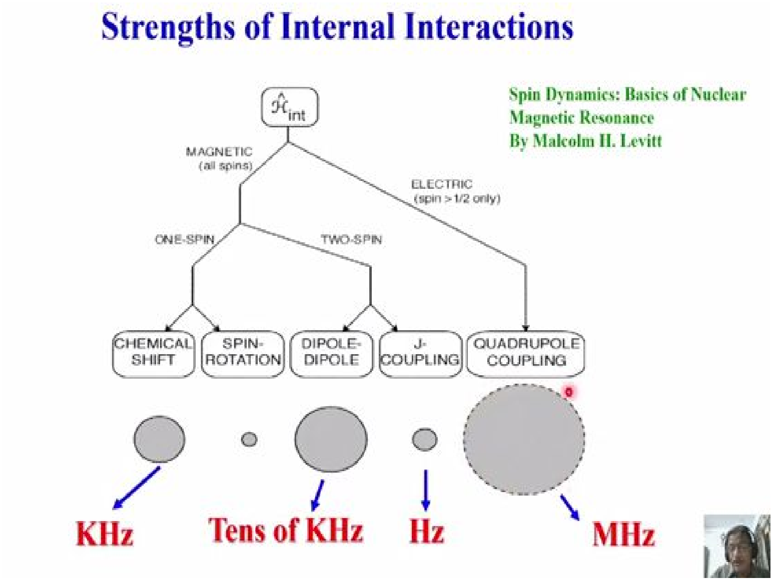

Strengths of Internal Interactions

Spin Dynamics: Basics of Nuclear Magnetic Resonance By Malcolm H. Levitt

Now, this is a picture which is taken from book of spin dynamics, basics of nuclear magnetic resonance by Malcolm Levitt, fantastic very beautifully he discussed many things, many concepts in that book. I suggest all of you please go through that book; it is a book worth reading and worth possessing. Lot of things have been discussed, he is one of the pioneers of NMR, you must read that. Now, he has given various types of elliptical or circular shapes, whatever you call.

This is a bigger one, bigger the size, larger the interaction. Remember this is very big, the quadrupolar coupling and this coupling strength is of the order of several megahertz, it can be of the order of few 10s of megahertz. Sometimes it can be 1 mega to 20, 30, 40, 50 megahertz also. The interactions strengths can be very large. But most of the cases, there are special nuclei where the quadrupolar interaction that is electric interaction overtakes the external Zeeman interaction, that is possible. But these are special types of nuclear if you study that.

In other cases, we are looking at these types of interactions. Of course this I told you quadrupolar interaction is quite large. But in the general case that what we are dealing with in the solution, state this is a perturbation term, that is a small term compared to Zeeman interaction. Remember it is a small term compared to Zeeman interaction. We treat this as a perturbation term. So this is quadrupolar perturbed Zeeman. If this is very, very large compared to Zeeman, then Zeeman perturbs this, we will not go more into the details of that.

And the J coupling, as I said through covalent bond, is as of the order of few hertz, it can be 5, 10 hertz between protons. Few 10s of hertz, few 100 Hz between 2 different hetero nuclei. So it is of the order of few hertz to 100 hertz. Dipole-dipole interaction that is the through space interaction is of the order of several 10s of kilohertz. That is very important, it can go from kilohertz 10, 20, 30, 40 kilohertz could be there, depending upon the orientation and the ordering, and the chemical shift is of the order of few kilohertz, 5 to 10 kilohertz, depending upon the type of nuclei.

Or it can be very large, if you go to some exotic nuclei like cobalt and others; it can be about 50, 60 kilohertz like that, much more. So, this gives a rough idea about the strengths of different types of interaction. Since we are not dealing with this, we are dealing with only these things. Ofcourse in his book, he has introduced spin rotation interaction, I am not bothered about it at the moment we are concentrating only on chemical shift, J coupling and dipole coupling and among these, dipole coupling has the largest strength, then chemical shift then comes J coupling.

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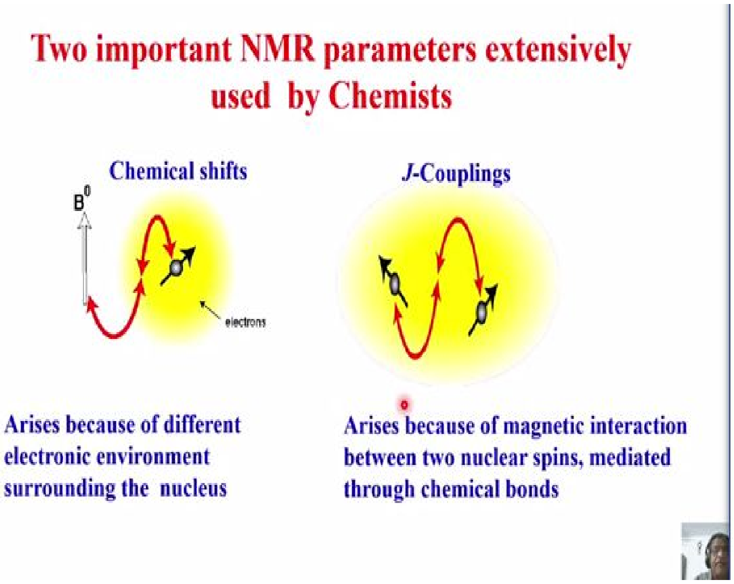

Two important NMR parameters extensively used by Chemists

Chemical shifts

J-Couplings

Arises because of different electronic environment surrounding the nucleus

Arises because of magnetic interaction between two nuclear spins, mediated through chemical bonds

Remember these, now of the 3 things, there are 2 very important parameters which are extensively used by chemists; that is chemical shift and J couplings. These chemical shifts arise because of different electronic environments around the nucleu,s I told you already. See, this is again the picture from Professor Malcolm Levitt book. In the magnetic field the nuclear spin is not bare, surrounded by electrons. This is going to shield this nucleus.

We will see about chemical shift shielding now, and this J coupling again there is a magnetic field because of the electrons surrounding it through bond this goes to through bond and finally got to this. This arises because of magnetic interaction between 2 nuclear spins mediated through covalent bond, remember this.

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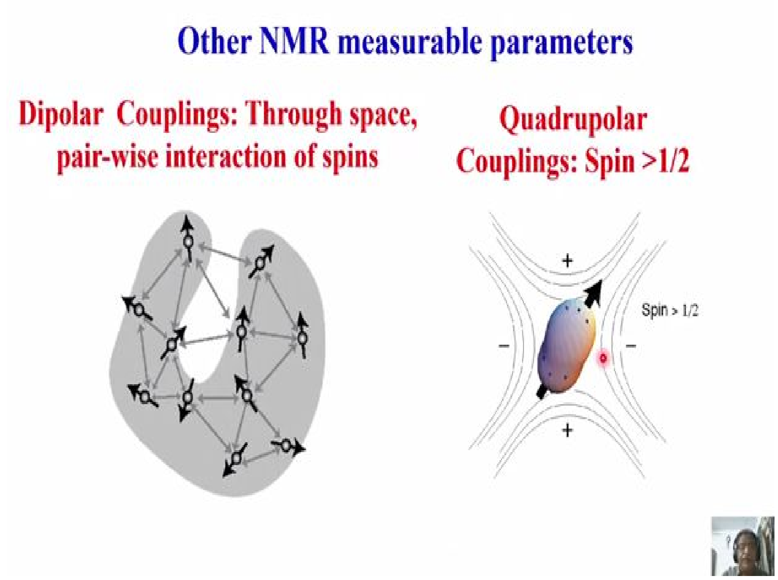

Other NMR measurable parameters

Dipolar Couplings: Through space, pair-wise interaction of spins

Quadrupolar Couplings: Spin >1/2

And there are other measurable parameters I told you, one is a dipolar coupling that is through space, which is pair-wise interaction of spins. That means, there n number of spins possible in a molecule, n number of protons are hetero nuclei is present, let us say. Each spin can interact with all the remaining spins depending upon their spatial proximity, understand. When we go further we will understand later, the previous interaction scalar coupling has certain strength beyond a certain number of chemical bond, the strength drastically decreases. And after a certain number of bonds, we do not see it. Whereas here, there may be n number of nuclear spins, no problem they one can interact with others so long as, there is a spatial proximity. The number of bonds there separated, that does not matter. The proximity is important and for this quadrupolar coupling, spin is greater than half I will not discuss this.

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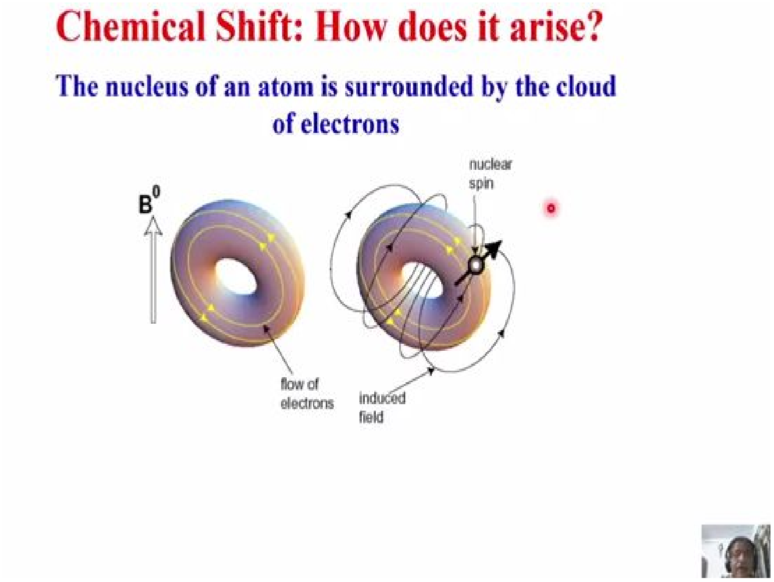

Chemical Shift: How does it arise?

The nucleus of an atom is surrounded by the cloud of electrons

Now we will worry about chemical shift, how does it arise and what is going to happen? We will discuss this in the next class.