One and Two Dimensional NMR Spectroscopy for Chemists

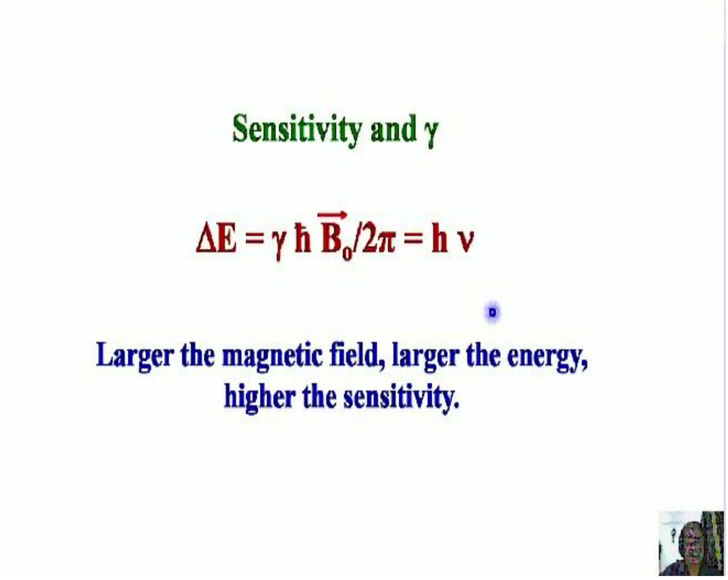
Prof. N. Suryaprakash
NMR Research Centre
Indian Institute of Science – Bengaluru

Lecture - 06

Inducing Resonance and Bulk Magnetization

Welcome back, in the last class, we discussed about the sensitivity of a NMR signal, and utilizing the Blotzmann equation, we worked out what happens to the sensitivity as a function of magnetic field, and what happens when we lower the temperature, we discussed.

(Refer Slide Time: 00:47)



Sensitivity and γ

$$\Delta E = \gamma \hbar \vec{B}_0 / 2\pi = h \nu$$

Larger the magnetic field, larger the energy, higher the sensitivity.

And we came to a situation, I also explained to you that sensitivity depends upon gyromagnetic ratio gamma. And of course, we know this delta E is given by this equation gamma h cross B0 / 2 pi, which is equal to hv. It means larger the magnetic field, larger the energy and higher the sensitivity.

(Refer Slide Time: 01:17)

Higher the γ, Higher the Sensitivity

^{1}H Nucleus has highest γ
among all the stable nuclei

^{1}H has highest sensitivity among all
the Stable NMR active nuclei

I also mentioned higher the gamma, higher the sensitivity, this is what we have to understand now. And of course we all know, among all this stable nuclei, I mentioned several times earlier also, the proton that is the one, which is the highest gamma. As a consequence, the detection of the proton signal is more sensitive compared to any other NMR active nuclei. I repeat, the sensitivity of the detection of the proton signal is much more compared to any other NMR active nuclei, because of its highest gamma.

(Refer Slide Time: 02:09)

Sensitivity depends on 3 factors

Magnetic moment (μ)
Population difference
Coil magnetic flux.

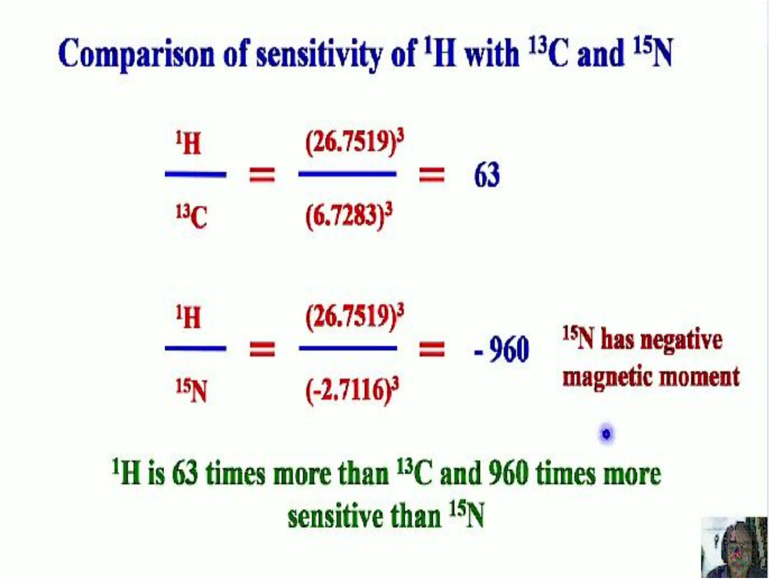
All these factors depend on γ

Thus sensitivity of a given nuclei is γ^3

Now the sensitivity depends upon 3 factors, one the magnetic moment μ, second, the population difference between the energy states and the magnetic flux induced in the coil. All these factors depend on gamma, each of these individual terms, depends on gamma. So what does it mean?

The total sensitivity thus, is given by gamma Q, it is depends upon gamma cube, because each of these depends upon gamma.

(Refer Slide Time: 02:58)



Comparison of sensitivity of ^{1}H with ^{13}C and ^{15}N

$$\frac{^{1}H}{^{13}C} = \frac{(26.7519)^3}{(6.7283)^3} = 63$$

$$\frac{^{1}H}{^{15}N} = \frac{(26.7519)^3}{(-2.7116)^3} = -960$$

^{15}N has negative magnetic moment

^{1}H is 63 times more than ^{13}C and 960 times more sensitive than ^{15}N

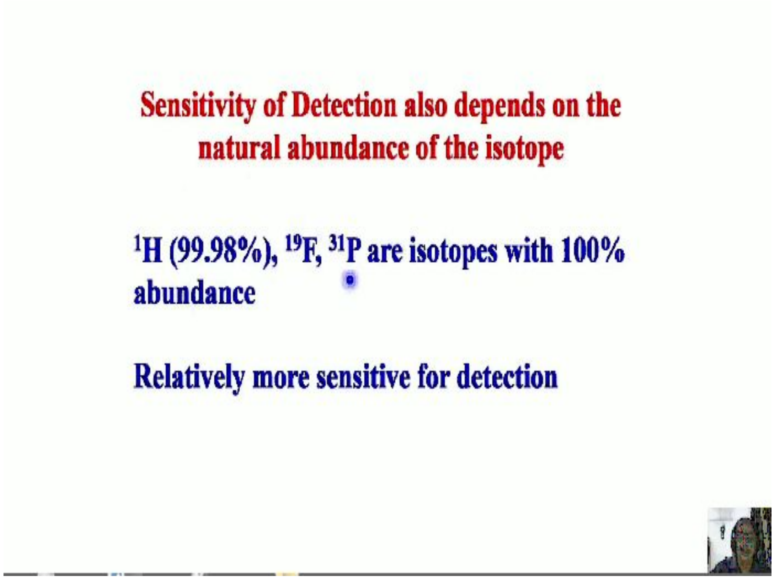
So now let us understand how the sensitivity depends for the different nuclei with a different gamma, compared to proton which is highly sensitive. In the sense relatively. Let us compare the sensitivity of proton with that of carbon and nitrogen 15. The ratio of sensitivity of proton to that of carbon is given by gamma cube of proton divided by gamma cube of carbon. Of course, we we also get other terms like into 10 to the power of 7 into radius per Tesla per second, because these 2 factors are same, both the numerator and the denominator and they get cancels all.

As a consequence, I am retaining only these 2 terms. So the 10 to the power of 7 term I removed it. So these are 2 just numbers, plug it into your calculator. You will find, this is 63. That means the sensitivity of carbon 13 compared to that of proton is 63 times lower. Remember, it is 63 times lower. What happens to nitrogen 15? Let us look at nitrogen 15, the same way we can calculate. Nitrogen 15 has a gamma, minus 2.7116.

Of course, yes it has negative magnetic moment. Now this negative as per the sensitivity is concerned when I am comparing the relative. I am not worried about this sign, but it is important in some experiments. Let us not worry about it right now, let us not worry about it, but it is important later. So this number, again plug these numbers into the calculator, you will find this is minus 960. So nitrogen 15 is even more less sensitive compared to that of proton.

If you have to detect that, nitrogen 15 compared to proton, it is really a difficult task because of it is extremely low sensitivity, relatively compared even that of carbon. Of course this sign, I said, is because of negative magnetic moment of nitrogen 15. So the general conclusion is, compared to proton detection, carbon is 63 times less sensitive and nitrogen 15 is 960 times less sensitive.

(Refer Slide Time: 06:02)



Sensitivity of Detection also depends on the natural abundance of the isotope

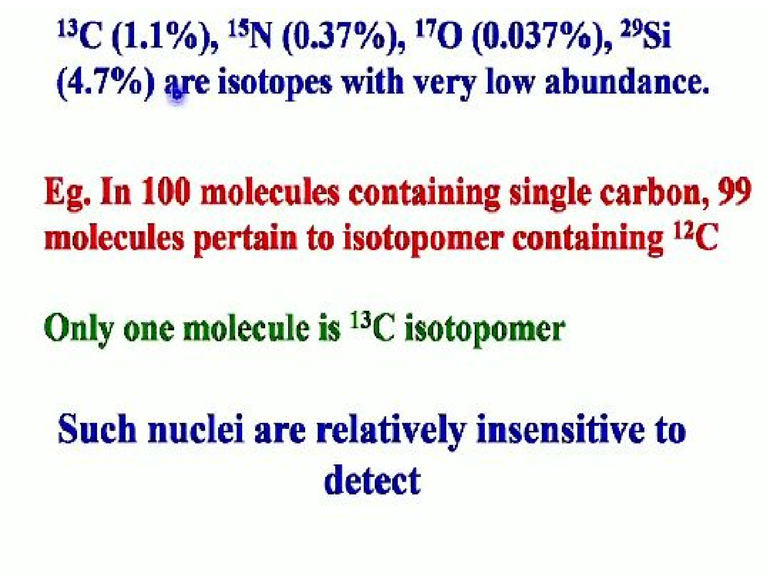
^{1}H (99.98%), ^{19}F, ^{31}P are isotopes with 100% abundance

Relatively more sensitive for detection

But another important factor which you must consider is the sensitivity of detection also depends on the natural abundance of the isotope. Remember, it also depends upon the natural abundance of the isotope. We all know some of these nuclei like proton is 99.98 percent abundant. Florine and phosphorus or isotopes with 100 percent abundance, of course I mean, more or less, you can consider all the 3 are 100 percent abundant, and these are relatively more sensitive for detection.

Of course, among the three, the proton is more sensitive, then florine, then phosphorus, because you remember I showed in one of the classes the table of properties of various NMR active nuclei, the gamma of proton and the gamma of fluorine are more or less nearly equal, but still less than that of proton. And the gamma of phosphorus is nearly 2.5 times less than that of proton. Understand the gamma phosphorus is 2.5 times less than that of proton. In spite of the fact they are 100 percent abundant, this is relatively more sensitive compared to the remaining fluorine and phosphorus 31, that I have taken as examples.

(Refer Slide Time: 07:42)



^{13}C (1.1%), ^{15}N (0.37%), ^{17}O (0.037%), ^{29}Si (4.7%) are isotopes with very low abundance.

Eg. In 100 molecules containing single carbon, 99 molecules pertain to isotopomer containing ^{12}C

Only one molecule is ^{13}C isotopomer

Such nuclei are relatively insensitive to detect

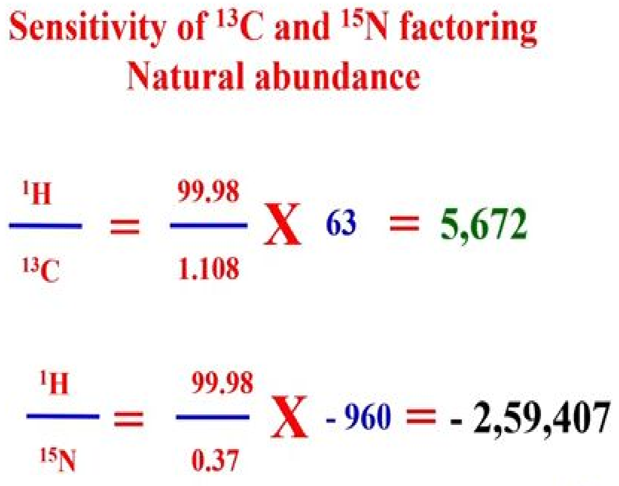
Let us look at some other nuclei. Carbon 13 1.1 percent abundant. Nitrogen 15 abundance is 0.37 percent, oxygen 17 even lower, silicon relatively better 4.7 percent. All these isotopes with very low natural abundance. There are many in the entire periodic table. I have just chosen a couple of them, as examples. What does it mean? What the sensitivity will tell us? What we understand from that? Of course, we discuss this as we go ahead in many classes.

Take for example, we have 100 molecules containing only one carbon, a single carbon I am talking. In that because carbon 13 is 1.1 percent abundant. And carbon 12 is 99 percent abundant. It means in 100 molecules 99 molecules pertain to isotopomer containing carbon 12. Only one molecule is carbon 13 isotopomer, remember if I have sample containing 100 molecules containing a single carbon, I will be detecting only one molecule in that.

These I took as an example, In a realistic situation we take sample and the volume of the sample NMR tube, which I will show you later, about 3 to 4 centimeter length we take, in a 5 millimeter inner diameter tube. You can calculate the volume, then you know you can calculate the number of molecules present using Avogadro number everything. In spite of that, you have to find out how many molecules, how many number of isotopomers will be there and their sample volume which contains carbon 13.

So even then the sensitivity of detection is much, much lower. As a consequence the detection of such low sensitive nuclei is even more difficult compared to that of proton, fluorine and phosphorus I mentioned, relatively they are much lower in sensitivity.

(Refer Slide Time: 10:19)



Sensitivity of ^{13}C and ^{15}N factoring Natural abundance

$$\frac{^{1}H}{^{13}C} = \frac{99.98}{1.108} \times 63 = 5,672$$

$$\frac{^{1}H}{^{15}N} = \frac{99.98}{0.37} \times -960 = -2,59,407$$

We recalculated the sensitivity of carbon and nitrogen relative to that of proton, at that time we did not take into account the natural abundance. We factor that also into the sensitivity calculation. What is going to happen? This factor we knew, we worked out using the gyromagnetic ratios, it was 63, the cube of gyromagnetic ratios. Now let us factor abundance also into account, taken that proton is 99.98, this is 1.108. If you multiply, plug these numbers into a calculator and it turns out to be around 5600 or 5700 is a number. That means taking all the factors into account, including natural abundance, the sensitivity of the detection of carbon 13 compared to that of protons is nearly 5700 times smaller, less sensitive. carbon 13 is nearly 5700 times less sensitive than that of proton. Let us look at nitrogen 15. Now bring in the abundance factor, it is 0.37. This turns out to be 259407, approximately 2.6 lakhs times less sensitive compared to proton. Imagine a detection sensitivity, how much difficult it is if you have to see the nitrogen 15 in natural abundance, when compared to proton. Nevertheless, nothing to worry we can detect nitrogen 15 in the present day spectrometers. Thanks to many developments, technological advancements, now we can even detect nitrogen 15 in natural abundance, of course but with little bit of difficulty. It is not absolutely impossible we can do that.

Of course, next other things, there are number of sensitivity enhancement techniques are also available in addition to what we can play with, like increasing the magnetic field, lowering the temperature, we also can think of few things which we can play with. For example, electronically, we can do some developments. That is, it is possible and we can take care of reducing the noise by using special probes called cryo probes, because when we are detecting the signal in the RF coil, we also invariably detect noise.

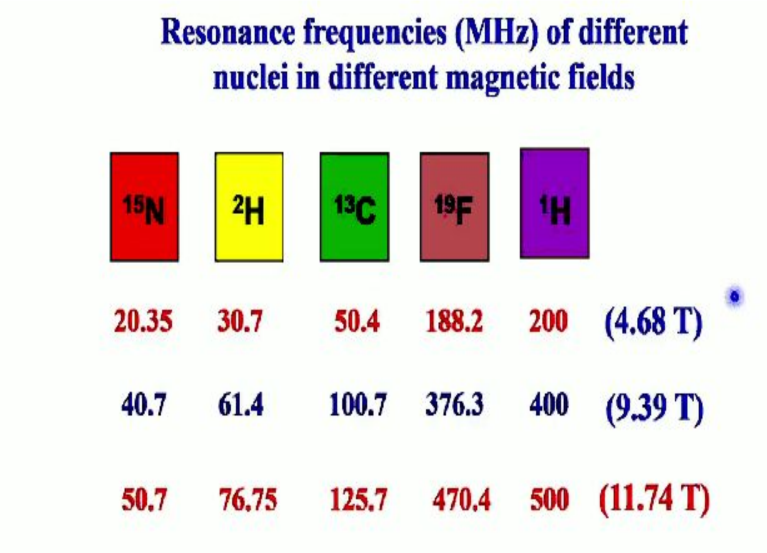
Noise also is part of the signal you are going to detect, this is called thermal noise. The thermal noise contains all the frequencies spread over the entire region of the spectrum. To overcome this difficulty, in the cryoprobes the RF coil is maintained at cryogenic temperature of liquid helium, which is 4.2 K. At that temperature, the thermal noise is quite a bit reduced.

Then the signal to noise ratio will significantly go up. Understand, that is a very important thing, in addition to that, can you do something experimentally? It is possible. There are a number of techniques we have, of course, we can design by understanding this spin dynamics. Some experimentally techniques have been developed, for example, polarization transfer technique.

It means we can transfer the magnetization of the abundant spin like proton, which is more sensitive, more sensitive means it has more magnetization, more that I will take that magnetization. I will tell you what is magnetization, as we go ahead. May be in this class or next class, we will discuss about bulk magnetization etc. Please remember the term magnetization, it is in simple terms you remember as the population difference, this has more population difference compared to other less abundant, less sensitive nuclei.

We can take that magnetization of protons, give to carbon or nitrogen which are less abundant or less sensitive. Then their sensitivity will go up. It is like taxing the rich and paying the poor. We can do that, tax the proton nuclei, take magnetization and give it to carbon and detect it, and you see that its sensitivity will go up. These are all experimental techniques. It is also possible. So we can understand some of these things as we go ahead in this course, in the next couple of classes.

(Refer Slide Time: 15:51)



Resonance frequencies (MHz) of different nuclei in different magnetic fields

^{15}N	^{2}H	^{13}C	^{19}F	^{1}H	
20.35	30.7	50.4	188.2	200	(4.68 T)
40.7	61.4	100.7	376.3	400	(9.39 T)
50.7	76.75	125.7	470.4	500	(11.74 T)

With this now let us look at resonance frequencies of different nuclei in different magnetic fields. This we have already discussed. Let us say I have to see 5 different nuclei in different magnetic fields. One, let us look at the magnetic field of 4.68 Tesla, in that proton resonates at 200 megahertz, carbon is 4 times smaller, 50 megahertz and nitrogen resonator 20 megahertz. keep increasing the magnetic field double it. Now it is double, all the resonant frequencies got doubled.

So in the high frequency spectrometer proton comes at 400 megahertz, carbon at 100 megahertz, nitrogen 15 at 40 megahertz. You can go ahead, at 11.74 Tesla proton comes at 500 megahertz, carbon at 125 megahertz and nitrogen 15 at 50 megahertz. This is an advantage, as you go to higher and higher frequencies, when you want to detect different nuclei, there are many advantages. The sensitivity will also go up, there is going to be a lot of chemicals shift dispersion also.

I will tell you what this chemical shift and everything, better you remember better resolution will be there. Spectral resolution will become much better as you go to higher and higher magnetic fields. Supposing if I go below, let us say 50 megahertz or 100 megahertz, the detection of nuclei at lower resonanating nuclei, like silver or barium and such nuclei whose resonant frequencies are much, much smaller, may be let us say at 300 or 400 megahertz, lead and other things, silver for example, may come at 5 or 10 megahertz or less than that.

Such nuclei, at that frequency if you want to detect, you get into problems, other problems, called acoustic ringing. When you have to detect low gamma nuclei, you get into what is called acoustic ringing. So on the other hand, we can partially address many of such problems by going to higher and higher magnetic fields.

(Refer Slide Time: 18:33)

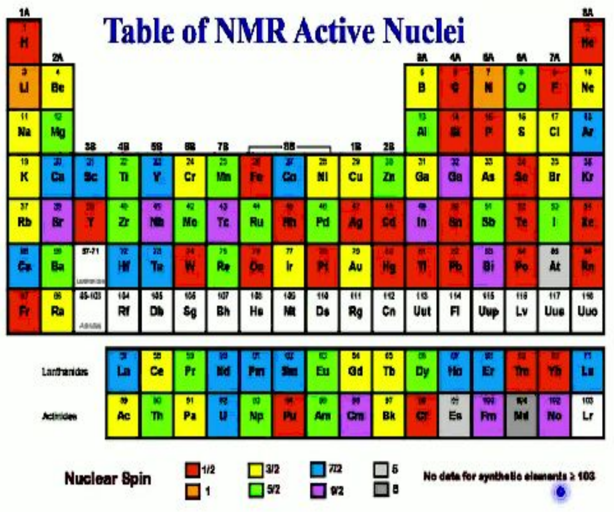


Table of NMR Active Nuclei

1A	2A	3B	4B	5B	6B	7B	8B			1B	2B	3A	4A	5A	6A	7A	8A
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	57-71	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	89-103	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Fl	Uup	Lv	Uus	Uuo

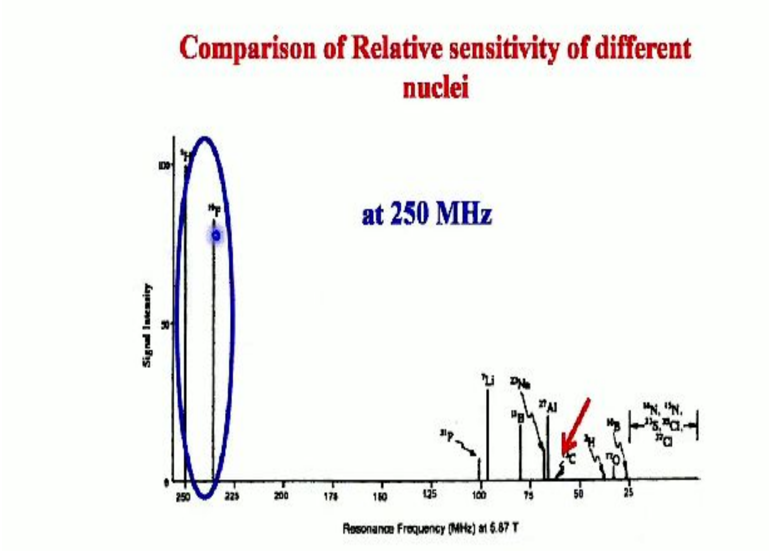
Lanthanides	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Actinides	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Nuclear Spin 🟥 1/2 🟧 1 🟨 3/2 🟩 5/2 🟦 7/2 🟪 9/2 ⬜ 5 ⬛ 6

No data for synthetic elements ≥ 103

Now, let us look at the table of NMR active nuclei. There are a number of nuclei which you can see which are NMR active. All of them are color and you can see the color code given here, this red color that is mean half nuclei, this yellow mean spin 3 / 2 nuclei, like that. You can see by and large, I do not know about what this is a white color whether they NMR active, or they have not been investigated or not, I do not know. By and large, you can see almost every element in this periodic table can be studied, because many of them, or most of them are NMR active.

(Refer Slide Time: 19:19)


Comparison of Relative sensitivity of different nuclei

at 250 MHz

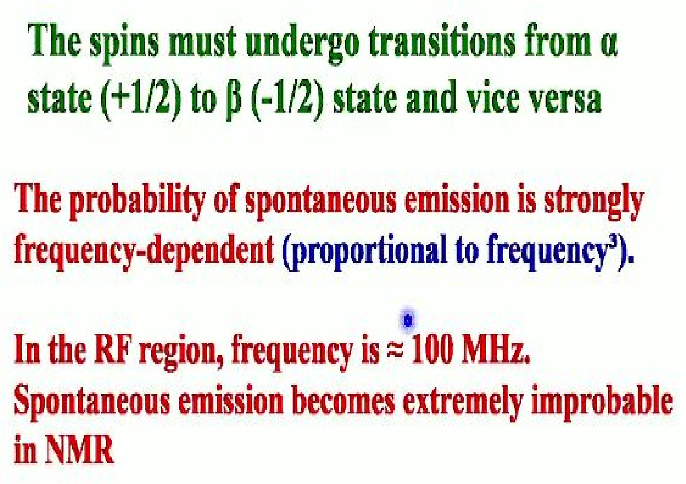
Let us compare the relative sensitivity of different nuclei, relatively. At let us say, 250 megahertz, if you have to compare the relative sensitivities for all the nuclei or selected nuclei. We take proton as the standard, as a reference, you know proton is highly sensitive as far as the detection is concerned, compared to all other nuclei. Let us call it 100 percent. Under identical conditions, when we record the spectrum of other nuclei, what will be their signal to noise ratio compared to that of proton?

If you see that, fluorine is almost about 80-85% less sensitive, sensitivity is 85% compared to that of proton. Come to this nuclei here, in this range. Look at carbon 13 which is another exotic nuclei which we always study. Organic chemistry people cannot do away with carbon, because carbon is present in the organic molecules. They have to see carbon nuclei apart from proton, but look at its sensitivity relative to that of proton, you can hardly see the signal.

Next Best is lithium, sodium and aluminum. They are very good. Boron, But come to this region. For example, nitrogen 14 or nitrogen 15, hardly you are seeing the signal relative to proton. So, this gives you an idea how less sensitive, other nuclei are and what are the difficulties involved if you want to detect such nuclei. These are the things, special attention is drawn for carbon and this is less sensitive compared to proton and fluorine.

Now, we understood in the 3 letters of NMR we discussed a lot about nuclear spins, okay spin physics we understood, we understood magnetism of the nuclear spins, but now we have to see the resonance. That means, we have to see the NMR peaks, NMR spectrum we have to see. How do you see that, we have to induce what is called resonance. What is that resonance? When 2 frequencies match we call it a resonance.

(Refer Slide Time: 22:04)



The spins must undergo transitions from α state (+1/2) to β (-1/2) state and vice versa

The probability of spontaneous emission is strongly frequency-dependent (proportional to frequency^3).

In the RF region, frequency is ≈ 100 MHz.
Spontaneous emission becomes extremely improbable in NMR

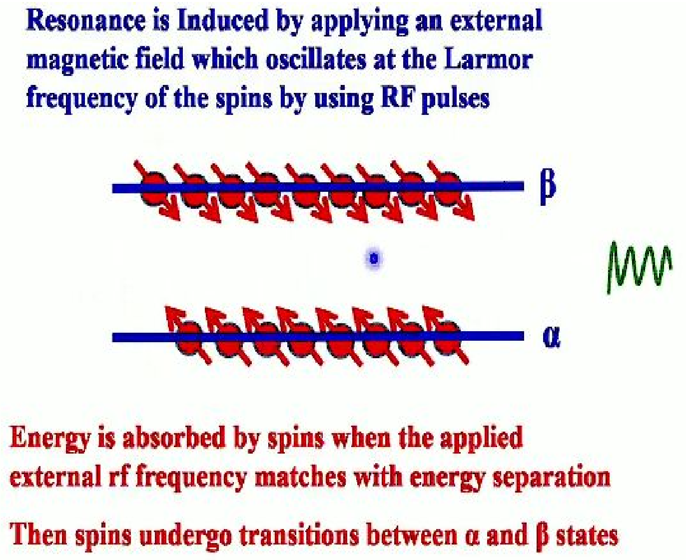
Now, how do you induce resonance here. When you want to see the resonance in NMR, the first condition is the spins must undergo transitions from alpha state to beta state and vice versa. We have 2 energy states let us say, for spin half nuclei, there are spins in this energy state, and there are spins in this energy state. that is what we have been discussing. And we also said there are more population, more spins in the lower energy state compared to that of higher energy state.

That is what we discussed, when we understood Boltzmann population distribution. But how do the spins undergo transition from alpha to beta state, or beta to alpha state? Remember, the probability of spontaneous emission is strongly frequency dependent. the spins have to undergo transitions, there are several ways, there are at least 2 or 3 ways which you must know. One is spontaneous emission from one state to another state, other is stimulated emission are stimulated absorption.

In the radio frequency region, because a spontaneous emission is proportional to frequency cube and which is of the 100 megahertz, in the radio frequency region the spontaneous emission probability is much, much lower. That is it a very low probability of spontaneous emission.

practically we can ignore it. then what is the next possibility? We have to think of stimulated absorption or stimulated emission. That is the only possibility, we have to think of.

(Refer Slide Time: 24:09)



Resonance is Induced by applying an external magnetic field which oscillates at the Larmor frequency of the spins by using RF pulses

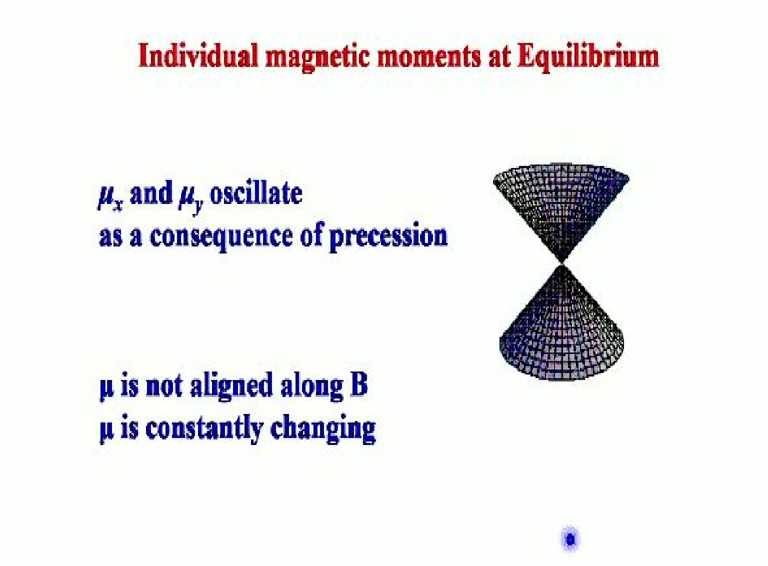
Energy is absorbed by spins when the applied external rf frequency matches with energy separation

Then spins undergo transitions between α and β states

How do you do that, let us say I have population distribution in two energy states like this, I have to induce resonance by stimulating absorption and emission by sending another radio frequency signal which is an oscillating one which oscillates at the larmor frequency. It must be an oscillating electromagnetic field, radio frequency, RF signal at the same frequency, it must be the Larmor frequency, only then the frequency matches, when the frequency matches what happens? You apply the radiofrequency pulse in a particular direction, that is in a direction perpendicular to the magnetic field, The spins absorb energy and then it go from lower energy state to higher energy state and come down from higher energy state to lower energy state. This is called transition. The transition takes place simultaneously from alpha to beta state and from beta to alpha state. This is called flipping of the spins from alpha to beta state and beta to alpha state, This is called resonance, when the incident radio frequency signal, RF, is at the larmor frequency. OK.

With this now I will introduce another term called random phase approximation and the concept of bulk magnetization. Remember, earlier one or 2 times I used the term magnetization and I said I will discuss it later, let us understand what is magnetization?

(Refer Slide Time: 26:13)



Individual magnetic moments at Equilibrium

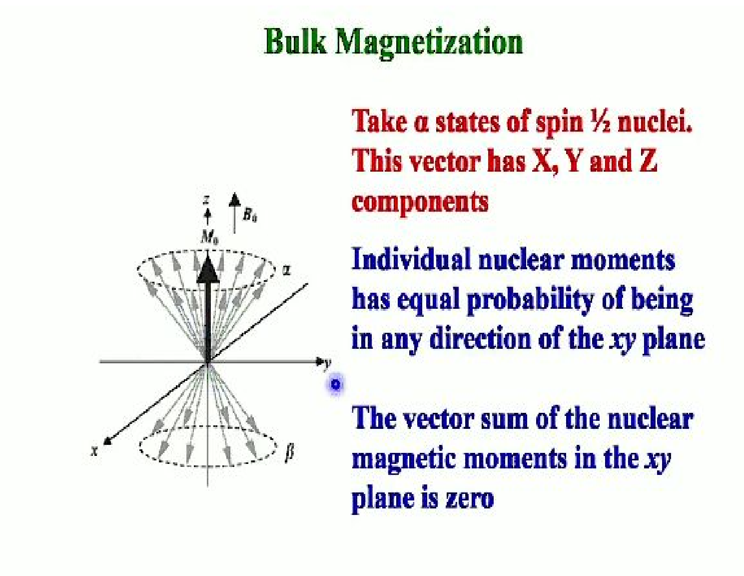
μ_x and μ_y oscillate
as a consequence of precession

μ is not aligned along B
μ is constantly changing

Let us consider individual magnetic moments at equilibrium. The magnetic moment means individual nuclear spins. Look at them, individual magnetic moments we knew, we have discussing many times, they are all aligned in two possible orientations for spin half nuclei, they have restricted orientation in the direction of the field, and in the direction opposite to that of the field. And in an external magnetic field, they undergo precession, Larmor position. There are millions and millions of such individual magnetic moments. They all start processing like this. and they precess like a cone, because it is making an angle in the direction of the magnetic field.

So, if I look at, even in thermal equilibrium condition, if I look at individual magnetic moments, they are not static, they are undergoing recession like this, and μ the magnetic moment, I said is a vector. you can resolve it into 3 components. X and Y and Z components. All these components μx and μy also start oscillating so much as a consequence of precession. and μ is not always aligned along B, it is constantly changing. That is individual magnetic moment is constantly changing orientation, because of precession.

(Refer Slide Time: 27:48)



Bulk Magnetization

Take α states of spin ½ nuclei. This vector has X, Y and Z components

Individual nuclear moments has equal probability of being in any direction of the *xy* plane

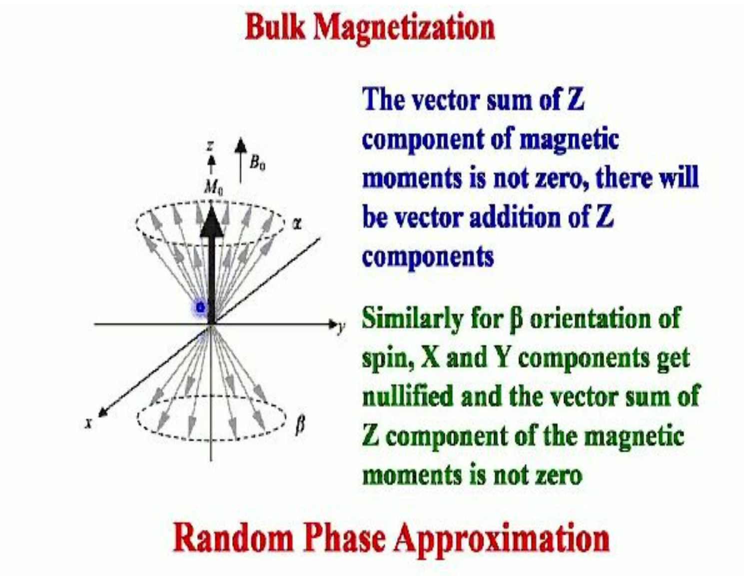
The vector sum of the nuclear magnetic moments in the *xy* plane is zero

But now, let us understand a little bit more taking only one of the magnetic moment, if we take only one of the magnetic moment. It has 2 states, alpha and beta states. Each is a vector. Now, we can resolve each vector into 3 components X, Y and Z. Let us take first example, the alpha, alpha state of the one of the magnetic moment, this orientation. This vector, now when we resolve into 3 components, these individual nuclei moments have all the probabilities.

If I take the individual components, there are X and Y components for this. Now I will take all of them together. What will happen? Each vector has X, Y and Z component because they are undergoing precession. X and Y, if I consider in the xy plane there is a every probability of these vectors in this xy plane, if there is a component along X axis or Y axis in this direction, you can always find another vector in the opposite direction.

When you take the vector addition of all of them, what will happen? Either the X component or Y component if you take, they get nullify. Each of them get nullified. So, as a consequence in the xy plane, the probability of finding these components is not there at all. It is 0. X and Y components are 0. The vector sum of the nuclei magnetic moments in the xy plane is totally 0. What about the Z component?

(Refer Slide Time: 29:57)



Bulk Magnetization

The vector sum of Z component of magnetic moments is not zero, there will be vector addition of Z components

Similarly for β orientation of spin, X and Y components get nullified and the vector sum of Z component of the magnetic moments is not zero

Random Phase Approximation

If I go to the Z direction here, the components of the Z direction are in the same direction. Look at it, they are not 0, they are all aligned in the same direction. Now, what you can do is, do is the vector addition of all of them, all these components, you do vector addition. Then you are going to get some magnetization vector. The vector addition as some value, which is sum of all those things. Thus some vector you are going to get, a big vector, after adding all these things.

Now, apply the same analogy for the beta component, that is beta orientation of the magnetic moment. Again, for all these, as I said, both these alpha and beta components are precessing in the form of a cone. Even for the beta component, the X and Y components get completely nullified. Both these components get nullified, the vector addition of X and Y components, even for this orientation, for all the magnetic moments is 0, the vector addition is 0.

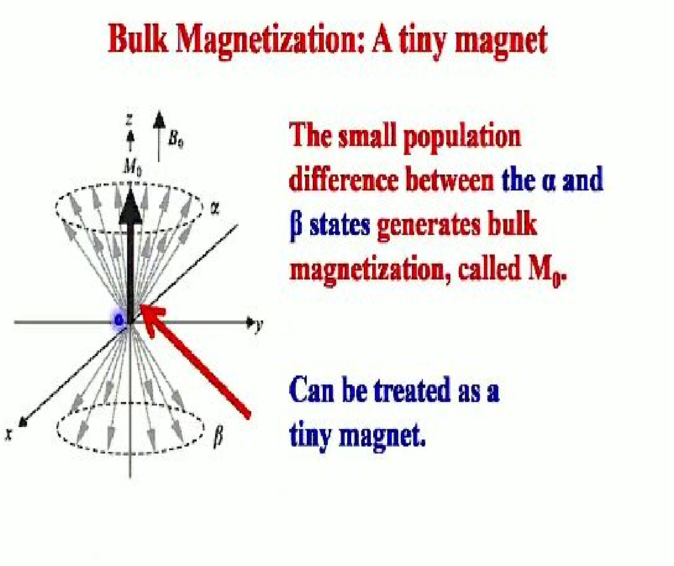
As a consequence, what will happen to this one, again Z one, - Z, that I say in the direction opposite to that at the magnetic field, the Z component is still there. There is some significant value of vector addition, which is nonzero. So, then both the directions along the Z and -Z direction, the vector addition has a component of the magnetization which is nonzero. Both are present in the Z axes. But we also know what happens.

We also know from our Boltzmann population distribution there are more spins in this direction than in this direction, than in the direction opposite to magnetic field. So it is a vector addition, if you take, this vector addition has a more magnitude than this one, the magnitude of the vectors added up here, I will say M alpha is more than M beta. So now again these 2 vectors are in the opposite direction M alpha and M beta.

If you add up these 2, the total vector some of in this direction, and the total vectors some in this direction because they are in the opposite direction, part of it gets nullified, but not completely, because there are more spins in this direction. So eventually, you are going to be left with some amount of magnetization, or vector sum of all these components in this direction. This is called magnetization.

It is called a bulk magnetization which is nothing but the vector sum of difference of magnetization from all the magnetic moments put together by an approximation called random phase approximation. As a consequence, all the components along the xy plane is 0, in the transverse plane and vector addition gives you a bulk magnetization which is nonzero in the direction of the magnetic field. You can treat this as a small tiny magnet. This is the concept of bulk magnetization.

(Refer Slide Time: 32:53)



Bulk Magnetization: A tiny magnet

The small population difference between the α and β states generates bulk magnetization, called M_0.

Can be treated as a tiny magnet.

Now, I am going to tell you what happens to this bulk magnetization in equilibrium, and how can you perturb it to detect the signal. So, this we have to understand, and we will discuss in the next class.