NMR Spectroscopy for Chemists and Biologists

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Lecture 50

Constant-Time COSY

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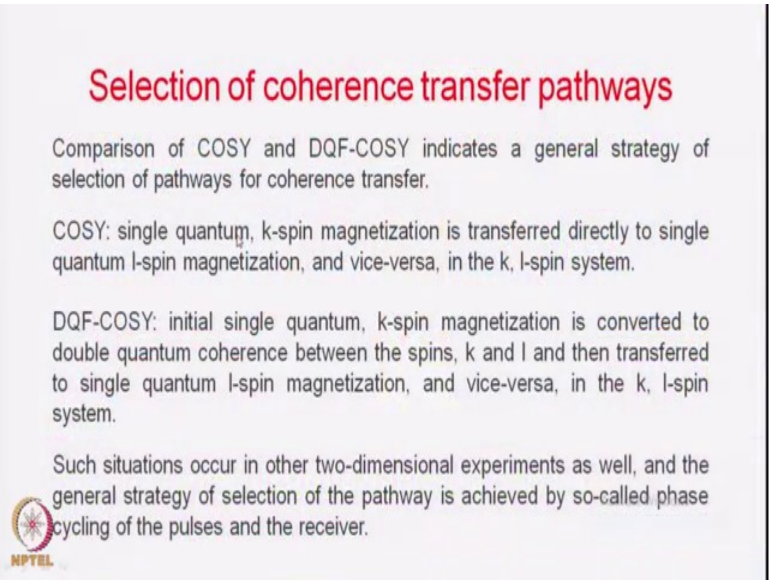

Selection of coherence transfer pathways

Comparison of COSY and DQF-COSY indicates a general strategy of selection of pathways for coherence transfer.

COSY: single quantum, k-spin magnetization is transferred directly to single quantum l-spin magnetization, and vice-versa, in the k, l-spin system.

DQF-COSY: initial single quantum, k-spin magnetization is converted to double quantum coherence between the spins, k and l and then transferred to single quantum l-spin magnetization, and vice-versa, in the k, l-spin system.

Such situations occur in other two-dimensional experiments as well, and the general strategy of selection of the pathway is achieved by so-called phase cycling of the pulses and the receiver.

So let us continue the discussion of two dimensional NMR Spectroscopy and this slide here is a summary of the previous few lectures which we have heard. Essentially it is giving you a concept the so called selection of coherence transfer pathways, it considers we discussed three experiments here, the COSY, double quantum filtered COSY and also the NOSY which is not listed here, but we discussed it in the last class.

In the COSY we had magnetization transfer in the following way, you started with a single quantum coherence of a particular spin let us say *k*-spin and the *k*-spin magnetization is transfer directly to single quantum *l*-spin magnetization. And similarly, for the *l*-spin magnetization is also transferred to the *k*-spin. So in the two-spin system the *kl* spin system. Same thing was applicable to more spins, a three-spin system or multiple spin systems, the same principle will apply.

I have discussed the various features of this spectrum, we said the diagonal peak has dispersive line shapes and all the components have in-phase character, the cross peaks have anti-phase character and they are absorptive line shapes, the dispersive line shapes was a disadvantage for the COSY spin because it reduces the resolution in the spectra, peaks which are closed to the diagonal become masked and will not be observed.

To circumvent this problem we developed this double quantum filtered COSY and here the pulse sequence is slightly modified instead of the two pulse experiment here this becomes a three-pulse experiment, we start with initial single quantum *k*-spin magnetization as before and this is now converted into double quantum coherence, it is not that the double quantum coherence is not created here, it is created after the first two pulses, but we actually ignored the one saying okay that is not observable therefore that is we do not need to consider that.

And here, we actually want to select that, we do not want to select the single quantum coherence as we have selected here, here we want to select double quantum coherence which is created between the two spins by the applications of the first two pulses and we use a strategy called as phase cycling where the phase of the pulses is cycled as *x,y, -x, -y* for the same t_1 increment and the receiver phase is appropriately adjusted so that the other components which are created here, the single quantum is eliminated, the *z* magnetization which is also created is eliminated and only the double quantum coherence is preserved.

But the double quantum signal is not observable as we have seen before, discuss it and therefore it has to be converted into observable magnetization and that is done by the third pulse which we apply in the double quantum filtered COSY pulse sequence. And then we observe the magnetization, the result of this is that the diagonal peak also gets in phase character and it has absorptive to line shapes, the cross peaks remain in phase and as anti-phase character and also remain absorptive to your line shapes.

Therefore, the diagonal and the cross peaks have both anti-phase magnetization and they have absorptive to your line shapes. This substantially improves the resolution in the spectrum and therefore, peaks which were lying very closed to the diagonal could be absorbed in the double quantum spectroscopy. In the third experiment which we can say that, that was the NOESY experiment where the z magnetization is selected, we through away the single quantum coherence that is created after the first two pulses and the double quantum coherence is also thrown away and zero quantum coherence which remains actually decays because of the long mixing time which is used in the NOESY pulse sequence.

And by suitable adjustment of the mixing time one could also eliminate the zero quantum coherence which was created in the three-pulse experiment this the NOESY is also three-pulse experiment and that only the *z* magnetization is retained at the end of the mixing time and this is then converted into single quantum coherence for observation. So here again the phase cycling is used, but the phase cycling that is used is different from the phase cycling that is used here.

And that is how we achieve the selection of different pathways of magnetization transfer through the pulse sequence that was an important concept which we developed and this is basically what I said so far is a summary of all of that in words.

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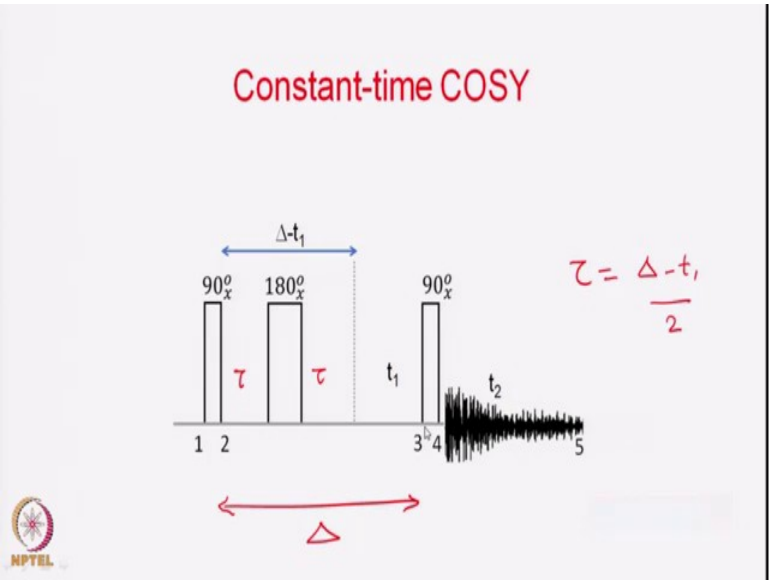

Constant-time COSY

$\tau = \frac{\Delta - t_1}{2}$

Now we go forward to explore other two-dimensional experiments and in that the one thing which comes most important which is used in may-many different kinds of multi-dimensional experiments and that is called as the constant time COSY and the pulse sequence for that is indicated here. So you start with a 90 degree *x* pulse, it could be 90*y* it does not matter, so we have just chosen here 90*x* pulse and this we have 180*x* pulse here and a 90*x* pulse here.

So we have here the first a 90 degree pulse, then you have a time period which is τ and this also Tau and now you notice that this is a spin echo so 90 τ, 180 τ is a spin echo right and this period is then followed by t1 and the total from here to here is constant. Total time from here to here is constant that is Δ and therefore $\tau=\Delta-\frac{t_1}{2}$, this is an interesting experiment. You see the time from here to here is kept constant.

Total time from here to here is kept constant and here is a component which is t_1 which is incremented from experiment to experiment and which also means that the τ also changes with t_1, this also is changing. Which means this 180 degree pulse keeps moving at time $t_1=0$ there is very first experiment you will see that this time is 0 and this 180 pulse will be in the middle of this delta period, of course at time $t_1=0$, $\tau=\frac{\Delta}{2}$ and this will be in the middle of this whole period Δ period.

Now as t_1 starts increasing, so this τ starts decreasing which means this 180 degree pulse keeps moving towards the left from the middle which was it was it starts moving towards left. So from experiment to experiment this 180 degree pulse keeps moving, okay. Now, how many increments then you can have here? See that is limited then by the Δ period. So once you reach a certain value of t_1 which is almost equal to Δ, then this 180 pulse will be almost adjacent to this first initial 90 degree pulse, you cannot increase it even beyond that.

Therefore, the number of t_1 increments you can do here is limited by what delta you choose, okay and how do you choose this delta? We chose this Δ depending upon how much signal you will have, so depending upon the relaxation times of this spin system what you might have the *k*-spin or the *l*-spin or whatever of the system what you might have the shortest t_2 and it will be dictated by that shortest t_2. So the signal will decay, the transverse magnetization will decay form here to here, we actually select the single quantum coherence here.

In this experiment we select the single quantum coherence, this is very similar to the COSY experiment except that we have a 180 degree pulse here and that creates what is called the spin echo part from here to here. So it is a single quantum magnetization as in the case of the COSY, but the period from here to here is constant that is delta and that limits how many increments you can have, the maximum value of t1 is limited by the total delta period what you might have.

When $t_{1\ max}$ is such that this $\tau = 0\,\Delta - \frac{t_1 max}{2}$ that is what the tau value if that becomes equal to 0 you cannot have t_1 incrementing after that okay. So that certainly will have an implication for the resolution along the F_1 axis in your experiment becomes the resolution in the x1 axis will depend upon what is that position time in the t_1 dimension okay. So but what are the advantages? Why do we do it?

And this we will see as you start looking at the explicit product operator calculation, this is the spin echo period here, the spin echo means you actually refocus the chemical shifts. Therefore, the chemical shifts evolution happens only for this period here t_1. Whereas the coupling evolution for a homonuclear system when you considering a homonuclear system the coupling evolution happens all the way from here to here because that is not dependent on the spin echo and for homonuclear system this 180 pulse is applied to both the spins or all the spins and therefore the coupling evolution continues to happen here and it will happen during that t_1 period as well.

So we will have the coupling evolution happening for the entire delta period which means the coupling evolution time is not dependent on the t1 because it is constant for every t_1 increment it is the same.

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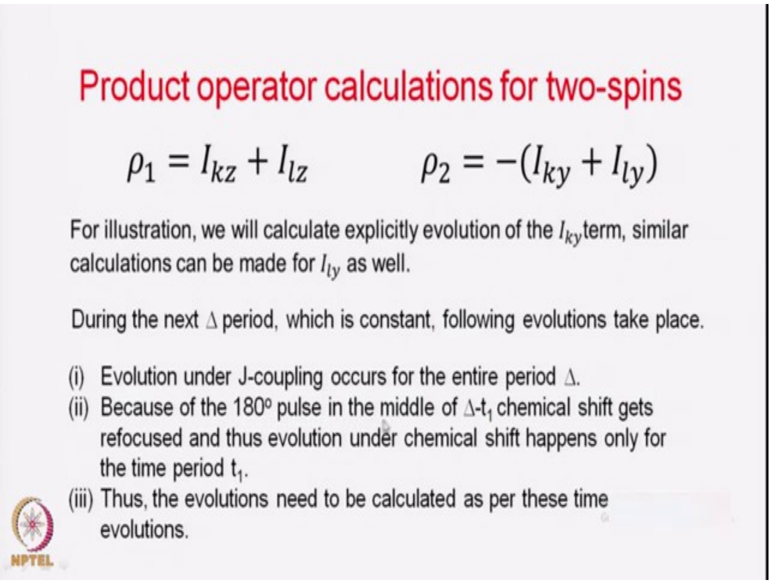

Product operator calculations for two-spins

$$\rho_1 = I_{kz} + I_{lz} \qquad \rho_2 = -(I_{ky} + I_{ly})$$

For illustration, we will calculate explicitly evolution of the I_{ky} term, similar calculations can be made for I_{ly} as well.

During the next Δ period, which is constant, following evolutions take place.

(i) Evolution under J-coupling occurs for the entire period Δ.
(ii) Because of the 180° pulse in the middle of Δ-t_1 chemical shift gets refocused and thus evolution under chemical shift happens only for the time period t_1.
(iii) Thus, the evolutions need to be calculated as per these time evolutions.

Whereas the chemical shift evolution happens only for the particular t_1 period, so let us look at the product operator calculations for a two spin system as we have done before for the other pulse sequences. For illustration we consider a two spin system, the initial density operator at ρ_1 is z magnetization of the two-spins,

$$\rho_1 = I_{kz} + I_{lz}$$

and once you apply the first $90x$ pulse you create the y magnetization of the two spins so

$$\rho_2 = -(I_{ky} + I_{ly})$$

Since these two are independent spins they evolve independently during the next evolution periods and to demonstrate the evolution we will consider the case spin evolution and the same thing can be applied to the l spin as well. Okay let us look at this I_{ky}, I_{ky} is y magnetization of the k-spin. Now during the next delta period which is constant the following evolution takes place.

Evolution under J-coupling occurs for the entire period Δ as mentioned to you, spin echo does not have any influence on that because it continues to evolve except it will have some implications for the line widths. The 180 degree pulse in the middle of the $\Delta - t_1$period the chemical shift gets refocused thus evolution under chemical shift happens only for the time period t_1. Thus, evolutions need to be calculated as per these time evolutions.

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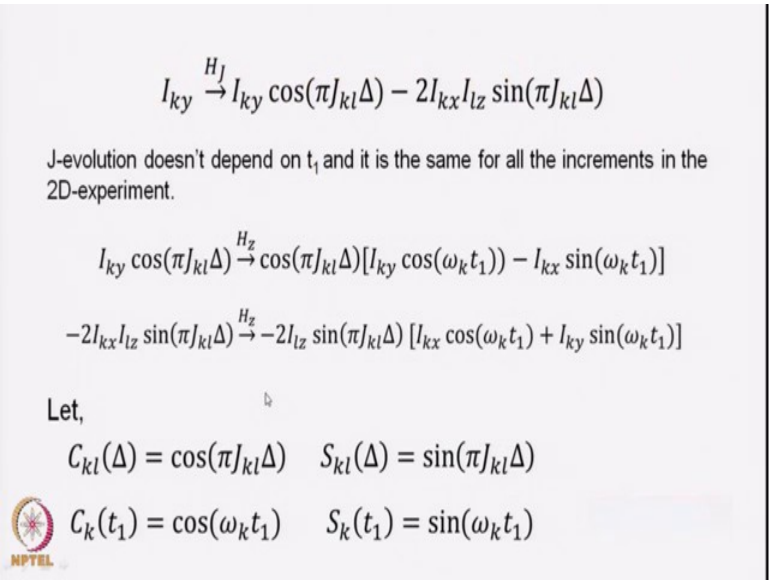

$$I_{ky} \overset{H_J}{\rightarrow} I_{ky}\cos(\pi J_{kl}\Delta) - 2I_{kx}I_{lz}\sin(\pi J_{kl}\Delta)$$

J-evolution doesn't depend on t_1 and it is the same for all the increments in the 2D-experiment.

$$I_{ky}\cos(\pi J_{kl}\Delta) \overset{H_z}{\rightarrow} \cos(\pi J_{kl}\Delta)[I_{ky}\cos(\omega_k t_1)) - I_{kx}\sin(\omega_k t_1)]$$

$$-2I_{kx}I_{lz}\sin(\pi J_{kl}\Delta) \overset{H_z}{\rightarrow} -2I_{lz}\sin(\pi J_{kl}\Delta)\,[I_{kx}\cos(\omega_k t_1) + I_{ky}\sin(\omega_k t_1)]$$

Let,

$C_{kl}(\Delta) = \cos(\pi J_{kl}\Delta)$ $S_{kl}(\Delta) = \sin(\pi J_{kl}\Delta)$

$C_k(t_1) = \cos(\omega_k t_1)$ $S_k(t_1) = \sin(\omega_k t_1)$

Let us look at that explicitly, consider the I_{ky} and we will first evolve J-coupling evolution, as I said we have seen before that it does not matter which one you consider first and which you consider later. Let us consider here the J evolution first, the Hamiltonian for J is H_J and which is

$$I_{ky} \overset{H_J}{\rightarrow} I_{ky}\cos(\pi J_{kl}\Delta) - 2I_{kx}I_{lz}\sin(\pi J_{kl}\Delta)$$

So clearly the J evolution does not depend on t_1 and it is the same for all the increments in the 2D experiment okay.

So, now let us consider the shift evolution of these two terms. The first term here which is

$$I_{ky}\cos(\pi J_{kl}\Delta) \overset{H_z}{\rightarrow} \cos(\pi J_{kl}\Delta)[I_{ky}\cos(\omega_k t_1)) - I_{kx}\sin(\omega_k t_1)]$$

The second term which is here this is

$$-2I_{kx}I_{lz}\sin(\pi J_{kl}\Delta) \overset{H_z}{\rightarrow} -2I_{lz}\sin(\pi J_{kl}\Delta)\,[I_{kx}\cos(\omega_k t_1) + I_{ky}\sin(\omega_k t_1)]$$

Now to simplify the symbols or the equations we use let us use some abbreviations here. So, let

$$C_{kl}(\Delta) = \cos(\pi J_{kl}\Delta) \quad C_k(t_1) = \cos(\omega_k t_1)$$

Similarly I write

$$S_{kl}(\Delta) = \sin(\pi J_{kl}\Delta) \quad S_k(t_1) = \sin(\omega_k t_1)$$

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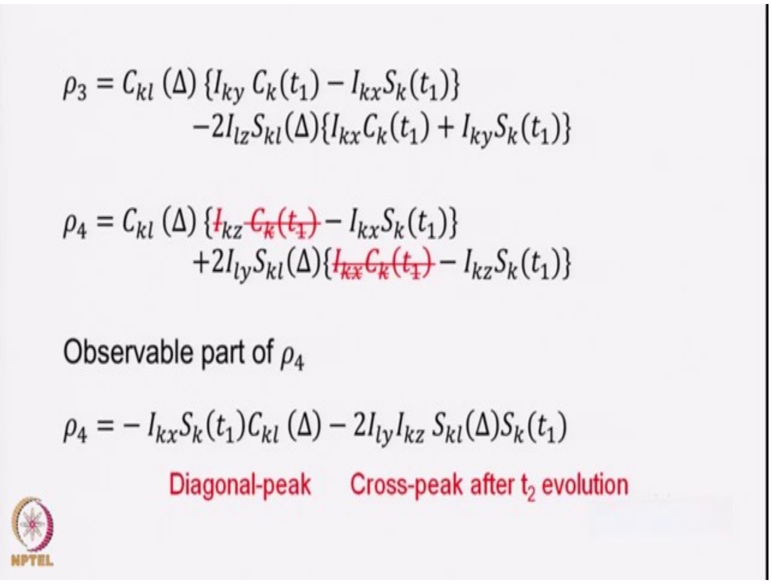

$$\rho_3 = C_{kl}(\Delta)\{I_{ky}C_k(t_1) - I_{kx}S_k(t_1)\}$$
$$-2I_{lz}S_{kl}(\Delta)\{I_{kx}C_k(t_1) + I_{ky}S_k(t_1)\}$$

$$\rho_4 = C_{kl}(\Delta)\{\cancel{I_{kz}C_k(t_1)} - I_{kx}S_k(t_1)\}$$
$$+2I_{ly}S_{kl}(\Delta)\{\cancel{I_{kx}C_k(t_1)} - I_{kz}S_k(t_1)\}$$

Observable part of ρ_4

$$\rho_4 = -I_{kx}S_k(t_1)C_{kl}(\Delta) - 2I_{ly}I_{kz}S_{kl}(\Delta)S_k(t_1)$$

Diagonal-peak Cross-peak after t_2 evolution

So with this notation, so what happens now? We consider the evolution at ρ_3 density operator at timepoint 3 pulse sequence, what is the timepoint 3 in the pulse sequence?

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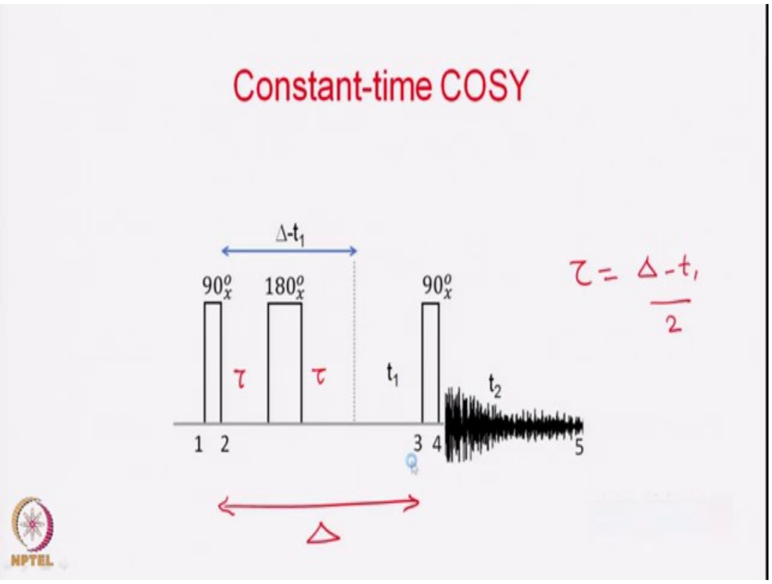

Constant-time COSY

That we are seeing here, this is the timepoint 3 in the pulse sequence. We consider up till now the evolution under *J* until here and we also consider the chemical shift evolution during this period here and therefore we consider the density operator at ρ_3.

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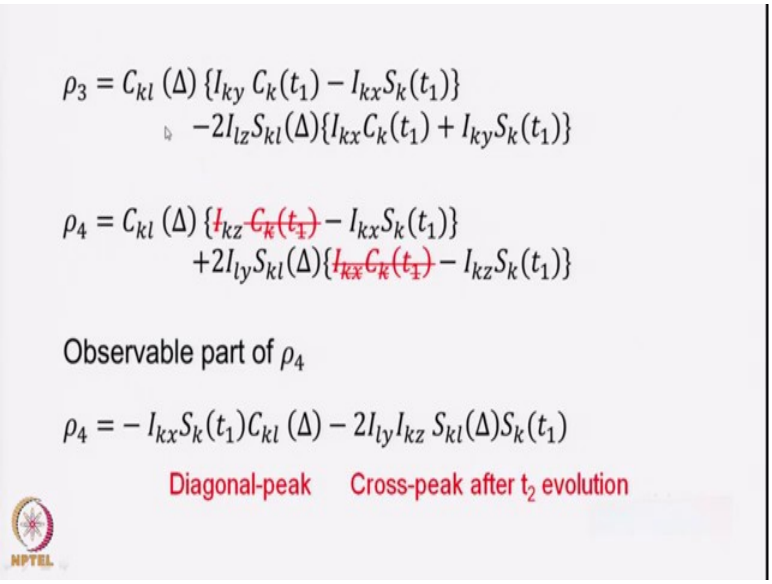

$$\rho_3 = C_{kl}(\Delta)\{I_{ky}C_k(t_1) - I_{kx}S_k(t_1)\} \\ -2I_{lz}S_{kl}(\Delta)\{I_{kx}C_k(t_1) + I_{ky}S_k(t_1)\}$$

$$\rho_4 = C_{kl}(\Delta)\{\cancel{I_{kz}C_k(t_1)} - I_{kx}S_k(t_1)\} \\ +2I_{ly}S_{kl}(\Delta)\{\cancel{I_{kx}C_k(t_1)} - I_{kz}S_k(t_1)\}$$

Observable part of ρ_4

$$\rho_4 = -I_{kx}S_k(t_1)C_{kl}(\Delta) - 2I_{ly}I_{kz}S_{kl}(\Delta)S_k(t_1)$$

Diagonal-peak Cross-peak after t_2 evolution

And the

$$\rho_3 = C_{kl}(\Delta)\{I_{ky}C_k(t_1) - I_{kx}S_k(t_1)\} \\ -2I_{lz}S_{kl}(\Delta)\{I_{kx}C_k(t_1) + I_{ky}S_k(t_1)\}$$

Now this is the z magnetization okay now at this point we have this z magnetization here and this one is actually double quantum and zero quantum coherence because they have this term, 2 I_{ly} I_{kx} term okay. So these ones are not directly observable, so what happens here, I mean this is theρ_4, this is the ρ_4 density operator. The ρ_4 density operator is obtained after applying the 90*x* pulse to this ρ_3 density operator and when you do the 90*x* pulse I_{ky} goes to I_{kz} and I_{kx} remains as I_{kx} and here I_{lz} goes to I_{ly} and this I_{kx} remains I_{kx} and this I_{ky} goes to I_{kz}.

Now here you see this is *z* magnetization which is not observable because we are not doing anymore pulses after that, we are directly detecting the signal, this term is not observable, this term is single quantum coherence of the *k*-spin, this is observable and this is double quantum and zero quantum mixture which we do not observe, which is not observable therefore we do not consider this for further treatment and this is the I_{ly} I_{kz} this is *l* magnetization anti-phase to *k*-spin and this also is as such it is not observable when it evolves in the t_2 period it becomes observable and therefore we retain this.

So keeping these observable parts, we write this observable part of ρ_4 is

$$\rho_4 = -\, I_{kx} S_k(t_1) C_{kl}\,(\Delta) - 2 I_{ly} I_{kz}\, S_{kl}(\Delta) S_k(t_1)$$

so this will evolve during the t_2 period with the frequency of *k*-spin and this will evolve during the t_2 period with the frequency of *l* and therefore this will produce me in the end a cross peak whereas this will produce me a diagonal peak okay, fine.

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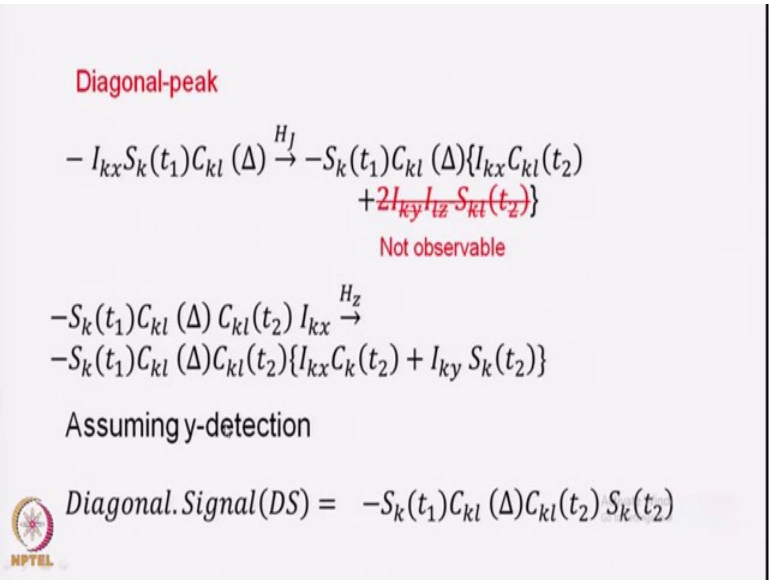

Diagonal-peak

$$- I_{kx}S_k(t_1)C_{kl}\,(\Delta) \overset{H_J}{\rightarrow} -S_k(t_1)C_{kl}\,(\Delta)\{I_{kx}C_{kl}(t_2) + \cancel{2I_{ky}I_{lz}\,S_{kl}(t_2)}\}$$

Not observable

$$-S_k(t_1)C_{kl}\,(\Delta)\,C_{kl}(t_2)\,I_{kx} \overset{H_z}{\rightarrow}$$

$$-S_k(t_1)C_{kl}\,(\Delta)C_{kl}(t_2)\{I_{kx}C_k(t_2) + I_{ky}\,S_k(t_2)\}$$

Assuming y-detection

$$Diagonal.Signal(DS) = \ -S_k(t_1)C_{kl}\,(\Delta)C_{kl}(t_2)\,S_k(t_2)$$

So let us look at this evolutions individually, let us look at the first term which is the diagonal peak so

$$- I_{kx}S_k(t_1)C_{kl}\,(\Delta) \overset{H_J}{\rightarrow} -S_k(t_1)C_{kl}\,(\Delta)\{I_{kx}C_{kl}(t_2) + \cancel{2I_{ky}I_{lz}\,S_{kl}(t_2)}\}$$

Now we first consider once again the coupling evolution here S_k t_1 C_{kl} (Δ) and the operator part is the I_{kx} which is evolving in t_2 gives me I_{kx} C_{kl} t_2 + 2 I_{ky} I_{lz} S_{kl} t_2 okay, so this has now generated therefore a term which is $2I_{ky}$ I_{lz} okay this is upto J evolution, the shift evolution is not going to make any difference in this with regard to whether it is anti-phase, it will not convert an anti-phase term and in-phase term.

Therefore, we can safely ignore this saying okay this is not observable in the t_2 period. But this term is observable. So this diagonal peak term keeps this I_{kx} here this is observable and this term is not observable, so therefore we can ignore this. Now let us consider the shift evolution of this after that, so I have the same here S_k t_1 C_{kl} (Δ) and $C_{kl\ t2}$ comes from here and the I_{kx} operator part evolves under the chemical shift as I_{kx} C_k t_2 + I_{ky} S_k t_2 using this abbreviation which we indicated there.

So this is $\cos\omega_k t_2$ and this is $\sin\omega_k t_2$. Now, if you assume without losing any generality we assume y detection, in which case the diagonal peak signal is given by this term, only keep this and we ignore this and therefore I will have here

$$Diagonal.Signal(DS) = \quad -S_k(t_1)C_{kl}\,(\Delta)C_{kl}(t_2)\,S_k(t_2)$$

So, now we notice that during the t_1 period I only have the chemical shift part right the S_k and there is no coupling because of the coupling part is evolving for a constant time and therefore there is no modulation of the signal due to coupling evolution during the delta period.

Therefore, this is only appear as amplitude modulation of the signal detected whereas t_1 dependent term results in a frequency when a Fourier transform it the t_1 dependence produces a frequency and this constant time evolution will not produce a frequency, it appears only as the amplitude modulation of this detected signal during the t_1 period. Along the t_2 period of course you have both the chemical shift evolution here and the coupling evolution and both are modulating the detected signal as a function of t_2. Therefore, when a Fourier transform along the t_2 dimension then I will have both the chemical shift and the coupling information and both once this have the sign terms okay.

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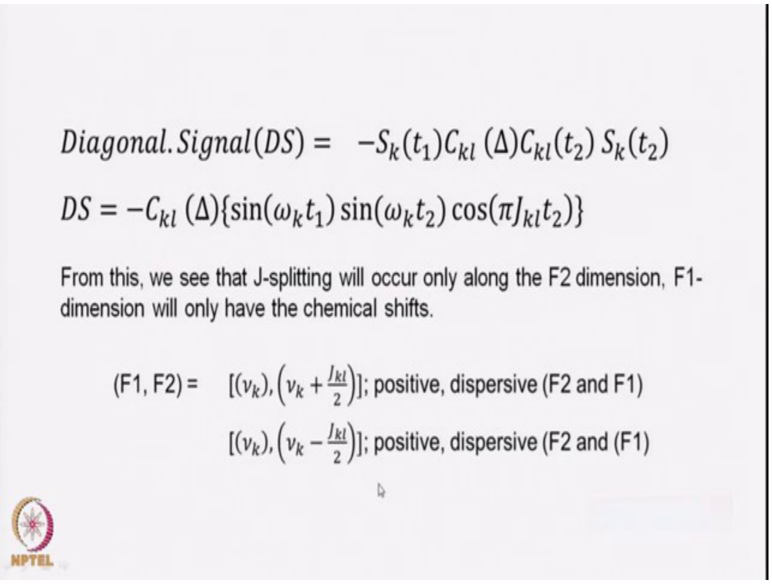

$$Diagonal.Signal(DS) = -S_k(t_1)C_{kl}(\Delta)C_{kl}(t_2)\,S_k(t_2)$$

$$DS = -C_{kl}(\Delta)\{\sin(\omega_k t_1)\sin(\omega_k t_2)\cos(\pi J_{kl} t_2)\}$$

From this, we see that J-splitting will occur only along the F2 dimension, F1-dimension will only have the chemical shifts.

(F1, F2) = $[(\nu_k), \left(\nu_k + \frac{J_{kl}}{2}\right)]$; positive, dispersive (F2 and F1)

$[(\nu_k), \left(\nu_k - \frac{J_{kl}}{2}\right)]$; positive, dispersive (F2 and (F1)

Let us expand this, so I have here the same expression diagonal signal is I have removed this I_{ky} because when you take the trace with I_{ky}, suppose that I_{ky} square y goes to 1 therefore the signal is only dependent on these coefficients. So the

$$Diagonal.Signal(DS) = -S_k(t_1)C_{kl}(\Delta)C_{kl}(t_2)\,S_k(t_2)$$

,

now if I expand this I have here $C_{kl}(\Delta)$ keep out this constant part which is the kind of an amplitude modulation as I said.

And this will be

$$DS = -C_{kl}(\Delta)\{\sin(\omega_k t_1)\sin(\omega_k t_2)\cos(\pi J_{kl} t_2)\}$$

From this we see that J splitting will occur only along the F_2 dimension and F_1 dimension will only have the chemical shift. After expanding this as before we have considered that I am writing here the final frequency distribution in the 2 dimensional plane. So, how many peaks I will get here? Along the F_1 dimension I will get 2 peaks because this one is $\sin\omega_k t_1$ and I will get at the frequency of ω_k, so single frequency at the frequency of ω_k.

Along the F_2 dimension I will have 2 peaks because when I expand this there will be two terms therefore I will get 2 peaks and this will be therefore F_1, F_2 will have the frequencies like this, the $v_k$here and this is F_1 dimension and this is $v_k + \frac{J_{kl}}{2}$ and the second peak will be v_k along F_1 dimension and F_2 dimension will be $v_k - \frac{J_{kl}}{2}$.

Therefore, there is a splitting here and the separation between them is the coupling constant and notice these both will be positive peaks and they will have the sine peak shape okay since they are sine modulation they will have dispersive line shapes here, so both of them will have dispersive line shapes along the F_2 and the F_1 dimension. Just now let us keep it that way and we will we that this actually can be changed by phase correction. We do a phase correction of course this can go to the absorptive line shape, but let us do it afterwards after we see the cross peak as well, okay.

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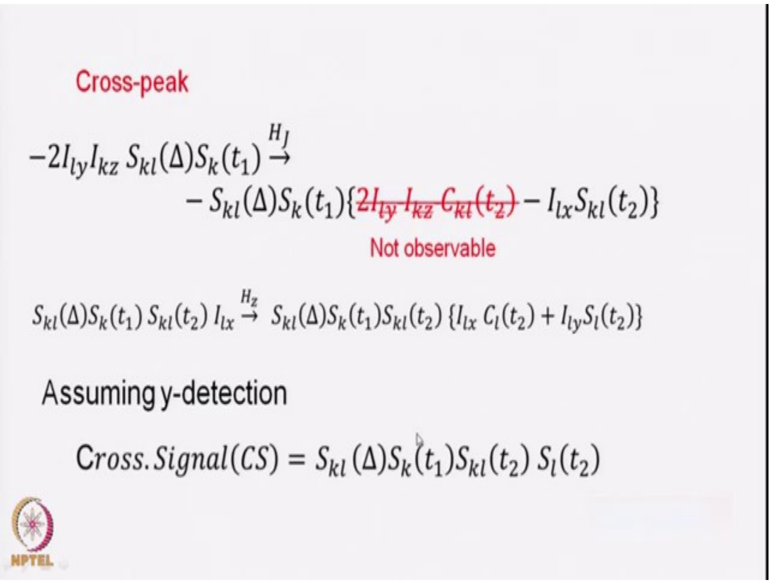

Cross-peak

$$-2I_{ly}I_{kz}\,S_{kl}(\Delta)S_k(t_1) \xrightarrow{H_J} -S_{kl}(\Delta)S_k(t_1)\{\cancel{2I_{ly}\,I_{kz}\,C_{kl}(t_2)} - I_{lx}S_{kl}(t_2)\}$$

Not observable

$$S_{kl}(\Delta)S_k(t_1)\,S_{kl}(t_2)\,I_{lx} \xrightarrow{H_z} S_{kl}(\Delta)S_k(t_1)S_{kl}(t_2)\,\{I_{lx}\,C_l(t_2) + I_{ly}S_l(t_2)\}$$

Assuming y-detection

$$Cross.Signal(CS) = S_{kl}\,(\Delta)S_k(t_1)S_{kl}(t_2)\,S_l(t_2)$$

Now, what happens to the cross peak? The cross peak is we have written the same function here as it evolves in the t_2 this is the initial term at the end of the t_1 period and after applying the 90 degree pulse and this is at the beginning of the detection period and we do the J coupling evolution here first along the t_2. So this will give me

$$-2I_{ly}I_{kz}\,S_{kl}(\Delta)S_k(t_1)\overset{H_J}{\rightarrow} - S_{kl}(\Delta)S_k(t_1)\{\cancel{2I_{ly}\,I_{kz}\,C_{kl}(t_2)} - I_{lx}S_{kl}(t_2)\}$$

Once again, we notice after the *J* evolution this is the anti-phase term which is not observable, it does not have a non-zero trace and therefore this will be non-observable and only this term will be observable okay, fine. Let us take that one here so

$$S_{kl}(\Delta)S_k(t_1)\,S_{kl}(t_2)\,I_{lx}\overset{H_z}{\rightarrow}\;S_{kl}(\Delta)S_k(t_1)S_{kl}(t_2)\,\{I_{lx}\,C_l(t_2) + I_{ly}S_l(t_2)\}$$

once again assuming *y* detection, because we have to be constant always the same, so *y* detection in one case we cannot have *x* detection in the other case. So you assume *y* detection there, you assume I detection here as well. So this cross signal will now be

$$Cross.Signal(CS) = S_{kl}\,(\Delta)S_k(t_1)S_{kl}(t_2)\;S_l(t_2)$$

So therefore, this will produce amplitude modulation because the coupling evolution during time $\Delta$and along the F_1 dimension when a Fourier transform you will only have the frequency $S_k\,t_l$ and this will produce me peaks along the F_2 dimension.

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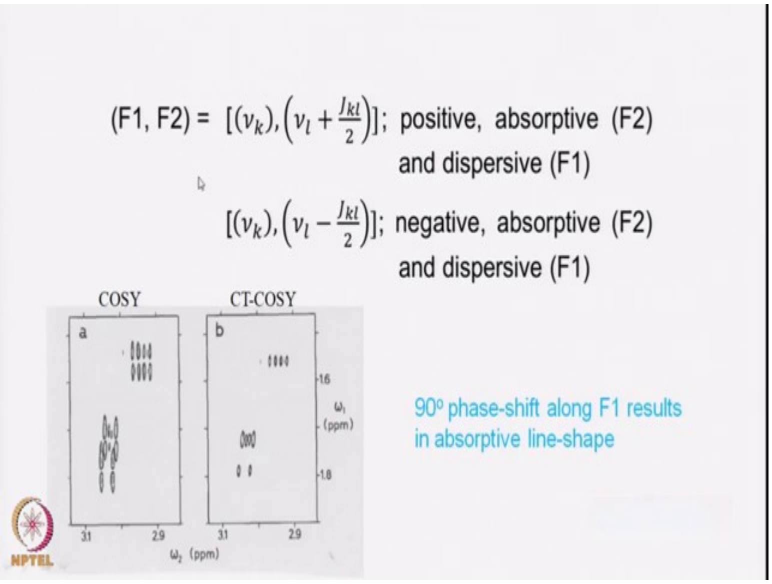

$$(\text{F1, F2}) = [(\nu_k),\left(\nu_l + \frac{J_{kl}}{2}\right)];$$ positive, absorptive (F2) and dispersive (F1)

$$[(\nu_k),\left(\nu_l - \frac{J_{kl}}{2}\right)];$$ negative, absorptive (F2) and dispersive (F1)

90° phase-shift along F1 results in absorptive line-shape

So now this one F_1, F_2 if I expand it I will get here like this v_k along F_1 dimension and $v_k+\frac{J_{kl}}{2}$ along F_2 at the frequency of this and v_k and $v_k-\frac{J_{kl}}{2}$ along the F2 dimension, so we will have 2 peaks here, but this because of the sign there this is these two will have opposite phases, so if this is positive, this will be negative but both are cosine terms and therefore this will produce me an absorptive peak along the F_2 dimension.

And notice this is absorptive along F_2, but this will be dispersive along F_1 because that was a sine term, $\sin \omega_k t_1$ it was and because along F_1 dimension I will have this ω_k frequency, this is the cross peak, you will have this ω_k frequency is dispersive line shape or the sine term and it is absorptive line shape along F_2, absorptive line shape along F_2, for both of these peaks and what was in the previous case for the diagonal peak?

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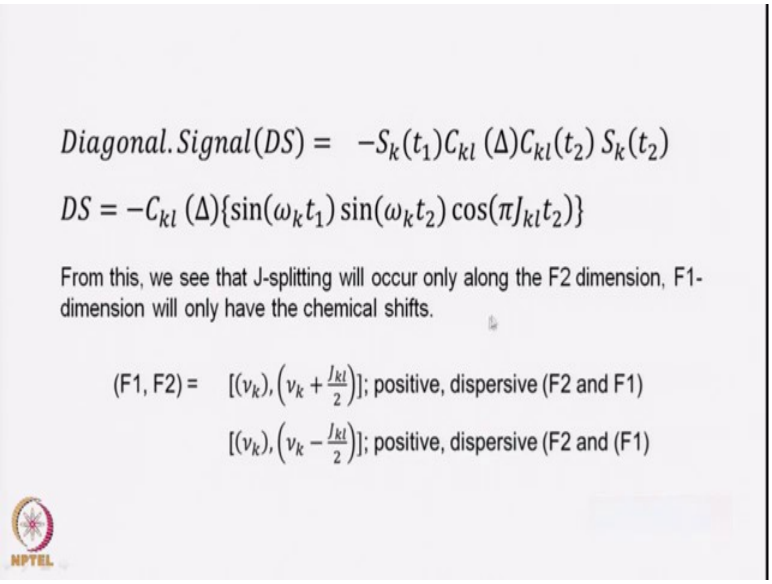

$$Diagonal.Signal(DS) = -S_k(t_1)C_{kl}(\Delta)C_{kl}(t_2)S_k(t_2)$$

$$DS = -C_{kl}(\Delta)\{\sin(\omega_k t_1)\sin(\omega_k t_2)\cos(\pi J_{kl} t_2)\}$$

From this, we see that J-splitting will occur only along the F2 dimension, F1-dimension will only have the chemical shifts.

(F1, F2) = $[(\nu_k), \left(\nu_k + \frac{J_{kl}}{2}\right)]$; positive, dispersive (F2 and F1)

$[(\nu_k), \left(\nu_k - \frac{J_{kl}}{2}\right)]$; positive, dispersive (F2 and (F1)

I had here the dispersive line shape along both F_2 and F_1 dimension okay, they were both positive here and the dispersive line shape along both and the F_1 dimension also there was dispersive.

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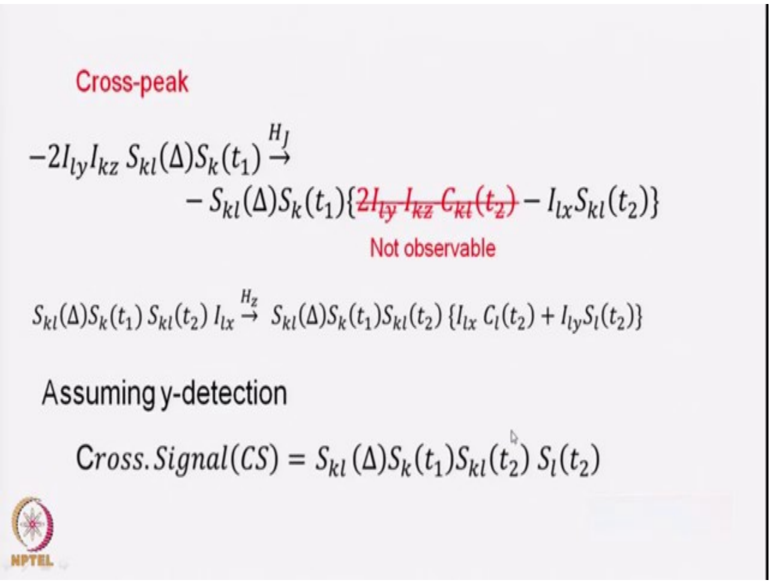


Cross-peak

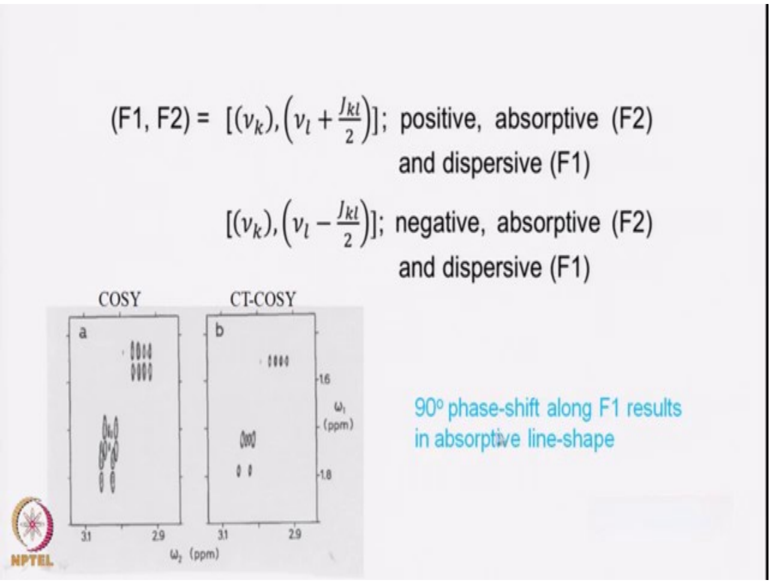
$$-2I_{ly}I_{kz}\,S_{kl}(\Delta)S_k(t_1)\xrightarrow{H_J}$$
$$-S_{kl}(\Delta)S_k(t_1)\{\cancel{2I_{ly}I_{kz}\,C_{kl}(t_2)}-I_{lx}S_{kl}(t_2)\}$$

Not observable

$$S_{kl}(\Delta)S_k(t_1)\,S_{kl}(t_2)\,I_{lx}\xrightarrow{H_z} S_{kl}(\Delta)S_k(t_1)S_{kl}(t_2)\,\{I_{lx}\,C_l(t_2)+I_{ly}S_l(t_2)\}$$

Assuming y-detection

$$Cross.Signal(CS)=S_{kl}\,(\Delta)S_k(t_1)S_{kl}(t_2)\;S_l(t_2)$$



$(F1, F2) = [(\nu_k),\left(\nu_l+\frac{J_{kl}}{2}\right)]$; positive, absorptive (F2) and dispersive (F1)

$[(\nu_k),\left(\nu_l-\frac{J_{kl}}{2}\right)]$; negative, absorptive (F2) and dispersive (F1)

90° phase-shift along F1 results in absorptive line-shape

So therefore, since this is the dispersive line shape along F_1 dimension for both diagonal and the cross peak I can apply the same phase correction for the F_1 dimension. So apply a 90 degrees phase shift along F_1, this will convert this dispersive line shape into absorptive line shape same true for the diagonal peak but we focus on the cross peak here. We are interested in looking at a cross peak. So if I do that then what I will have? I will have absorptive line shape along F_1 and absorptive line shape along F_2, I do not do any phase correction along the F_2 dimension.

Therefore, I will have absorptive line shape here and absorptive line shape along the F_1 dimension here. Now look what is a consequence of that? If you look at the comparison this is an experimental spectrum, a particular cross peak region. The cross peak region, this is the COSY spectrum and this is the constant time COSY spectrum and you see here, these peaks are completely overlapping, you cannot separate these, okay and here of course there is splitting here along the F_1 dimension as well and that has gone because we have removed the coupling along the F_1 dimension.

So this multiplicity along the F_2 dimension remains so the same 4 peaks are present but the peak appear at the center here across that chemical shift is remaining and the coupling is removed the along the F_2 and here there are 2 peaks which are overlapping and those got separated in this constant time COSY, okay therefore this one is called as ω_1 decoupled COSY, you may call it as constant time COSY but you can also call it as ω_1 decoupled COSY.

And this improves the resolution along the F_1 dimension in the cross peak area because we want to look at the cross peak fine structure and wherever we can measure this we can actually measure the coupling constants very well, that is the advantage of the constant time COSY and therefore, this component has been used in many-many multi-dimensional experiment, this is used as a entity which is inserted at various places to obtain high resolution along the indirect dimension.

And this becomes important even though I have eliminated t_1 *max* because I removed the coupling information here, this becomes quite beneficial and improves the resolution in the spectra and measures the chemical shift position precisely and the coupling constants you can measure along the F_2 dimension. So with that we will stop here and we continue with the other experimental sequences in the next class.