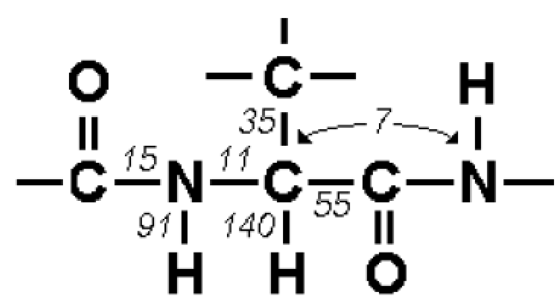
1D- and 2D-building blocks

The coherence transfer pathway of a typical NMR building block.

exp.	**coherence transfer**	**comment**
spin-echo	$-I_y \Rightarrow 2I_xS_z$	$J_{IS} > 0$ and $\tau=1/(4J_{IS})$
	$2I_xS_z \Rightarrow I_y$	
	$-I_y \Rightarrow -I_y$	$J_{IS} = 0$
INEPT	$-I_y \Rightarrow 2I_zS_y$	$J_{IS} > 0$
ref. INEPT	$-I_y \Rightarrow -S_y$	$J_{IS} > 0$
rev. INEPT	$2I_zS_y \Rightarrow -I_y$	$J_{IS} > 0$
ref. rev. INEPT	$-S_y \Rightarrow -I_y$	$J_{IS} > 0$
COSY	$-I_y \Rightarrow -2I_zS_y\sin(\Omega_I t)\sin(\pi J_{IS} t)$	$J_{IS} > 0$ (off diagonal)
TOCSY	$-I_y \Rightarrow S_x$	$J_{IS} = 0$ (off diagonal)
HMQC	$-I_y \Rightarrow -I_y\cos(\Omega_s t)$	$J_{IS} > 0$
HSQC	$-I_y \Rightarrow I_x\cos(\Omega_s t)$	$J_{IS} > 0$

As homonuclear coupling const. (J_{IS}) is small ≈ 10 Hz, the associated Δ and/or τ ≈ 1/10 Hz ≈ 100 ms, a longer delay time
As heteronuclear coupling const. (J_{IS}) is large ≈ 100 Hz, the relevant Δ and/or τ ≈ 1/100 Hz ≈ 10 ms, a rather short time.

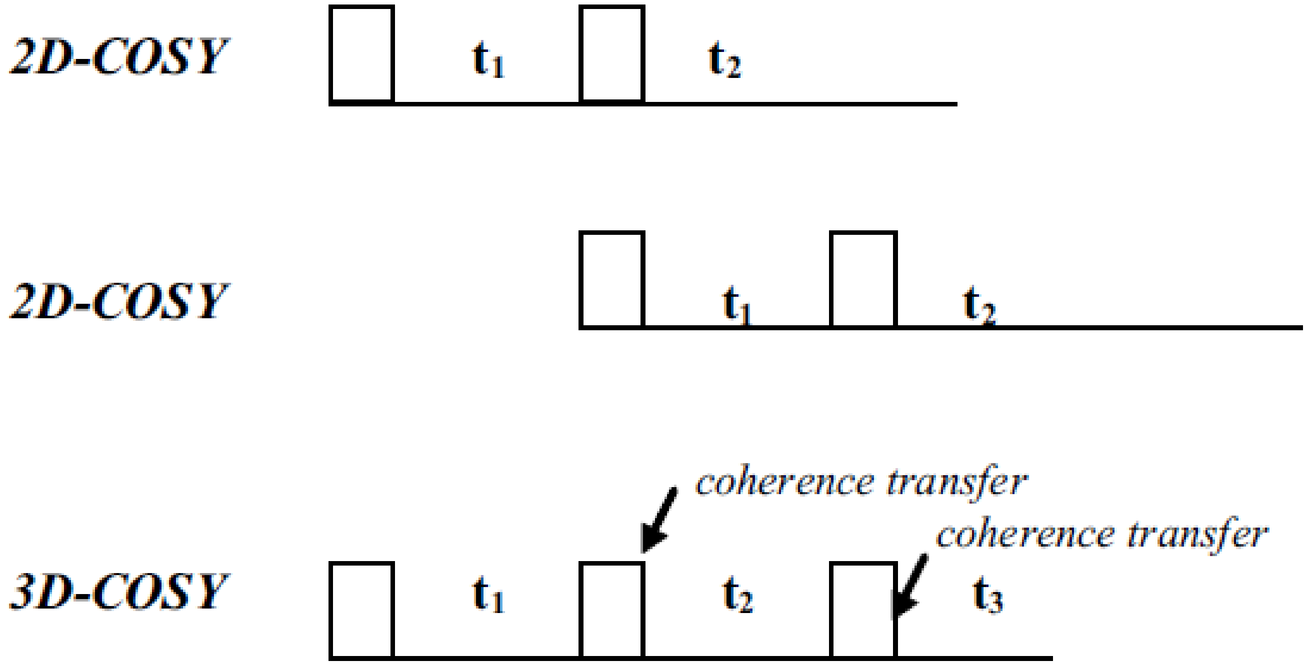
e.g. $J_{NH} \approx 90$ Hz or $J_{CH} \approx 140$ Hz



The simplest but „not too useful” 3D NMR experiment: the COSY-COSY

Homonuclear 3D NMR

Combining two *convenient* 2D experiments (e.g. 2D-COSY)



σ[eq.] $\quad I_z$ $\quad$ AMX (ISM) spin system

$\hat{H} = \pi/2 \ (\hat{I}_x)$ $\quad \downarrow 90°_x$

$-I_y$

$\hat{H} = \hat{I}_z(\Omega_I t_1)$ $\quad \downarrow t_1$

$-I_y \cos(\Omega_I t_1) + I_x \sin(\Omega_I t_1)$

$\hat{H} = 2\hat{I}_z\check{S}_z(J_{IS}\pi t_1)$ $\quad \downarrow$

$-I_y \cos(\Omega_I t_1) \cos(\pi J_{IS} t_1) \ +2I_x S_z \cos(\Omega_I t_1) \sin(\pi J_{IS} t_1)$
$+I_x \sin(\Omega_I t_1) \cos(\pi J_{IS} t_1) \ +2I_y S_z \sin(\Omega_I t_1) \sin(\pi J_{IS} t_1)$

$\hat{H} = \pi/2 \ (\hat{I}_x + \hat{S}_z)$ $\quad \downarrow 90°_x$

$-I_z \cos(\Omega_I t_1)\cos(\pi J_{IS} t_1) -2I_x S_y \cos(\Omega_I t_1)\sin(\pi J_{IS} t_1)$
$+I_x \sin(\Omega_I t_1)\cos(\pi J_{IS} t_1) -2I_z S_y \sin(\Omega_I t_1)\sin(\pi J_{IS} t_1)$

The $-2I_z S_y$ term is a single quan. S coher. originating from spin I. Thus the evolution of this term is followed:

$\hat{H} = \hat{S}_z(\Omega_S t_2)$ $\quad \downarrow t_2$

$-2I_z S_y \sin(\Omega_I t_1) \sin(\pi J_{IS} t_1) \cos(\Omega_S t_2) +2I_z S_x \ \sin(\Omega_I t_1) \sin(\pi J_{IS} t_1) \sin(\Omega_S t_2)$

$\hat{H} = 2\hat{S}_z M_z(J_{IS}\pi t_1)$ $\quad \downarrow$

$-2I_z S_y \sin(\Omega_I t_1) \sin(\pi J_{IS} t_1) \cos(\Omega_S t_2) \cos(\pi J_{SM} t_2)$
$+4I_z S_x M_z \sin(\Omega_I t_1) \sin(\pi J_{IS} t_1) \sin(\Omega_S t_2) \sin(\pi J_{SM} t_2)$

$+2I_z S_x \sin(\Omega_I t_1) \sin(\pi J_{IS} t_1) \cos(\Omega_S t_2) \cos(\pi J_{SM} t_2)$
$+4I_z S_y M_Z \sin(\Omega_I t_1) \sin(\pi J_{IS} t_1) \sin(\Omega_S t_2) \sin(\pi J_{SM} t_2)$

$-2\mathbf{I}_z\mathbf{S}_y \sin(\Omega_I t_1) \sin(\pi J_{IS} t_1) \cos(\Omega_S t_2) \cos(\pi J_{SM} t_2)$
$+4I_z\mathbf{S}_x M_z \sin(\Omega_I t_1) \sin(\pi J_{IS} t_1) \sin(\Omega_S t_2) \sin(\pi J_{SM} t_2)$

$+2\mathbf{I}_z\mathbf{S}_x \sin(\Omega_I t_1) \sin(\pi J_{IS} t_1) \cos(\Omega_S t_2) \cos(\pi J_{SM} t_2)$
$+4I_z\mathbf{S}_y M_Z \sin(\Omega_I t_1) \sin(\pi J_{IS} t_1) \sin(\Omega_S t_2) \sin(\pi J_{SM} t_2)$

$\hat{H} = \pi/2\ (\hat{S}_x + M_X)$ $\downarrow 90°_x$

$-2\mathbf{I}_z\mathbf{S}_z \sin(\Omega_I t_1) \sin(\pi J_{IS} t_1) \cos(\Omega_S t_2) \cos(\pi J_{SM} t_2)$
$-4I_z\mathbf{S}_x M_y \sin(\Omega_I t_1) \sin(\pi J_{IS} t_1) \sin(\Omega_S t_2) \sin(\pi J_{SM} t_2)$

$+2\mathbf{I}_z\mathbf{S}_x \sin(\Omega_I t_1) \sin(\pi J_{IS} t_1) \cos(\Omega_S t_2) \cos(\pi J_{SM} t_2)$
$-4I_z\mathbf{S}_z M_y \sin(\Omega_I t_1) \sin(\pi J_{IS} t_1) \sin(\Omega_S t_2) \sin(\pi J_{SM} t_2)$

The $-4I_z\mathbf{S}_z M_y$ term is a single quan. M coher. originating from spin I passed trough S.
Thus the evolution of this term is followed:

$$-4I_z S_z M_y \sin(\Omega_I t_1) \sin(\pi J_{IS} t_1) \sin(\Omega_S t_2) \sin(\pi J_{SM} t_2)$$

During ACQ:

$\hat{H} = M_z(\Omega_M t_3)$ $\downarrow$ t_3

$\hat{H} = 2\hat{S}_z M_z(J_{SM} \pi t_3)$ $\downarrow$

explanation: record at a fix t_1 a “normal” 2D-COSY where -the acquisition dim is t_3
-the freq. lab. period is t_2

↓

increase t_1 ←

↓ $t_1 + n$ (dw) n=1,2,…k (e.g. k=32)

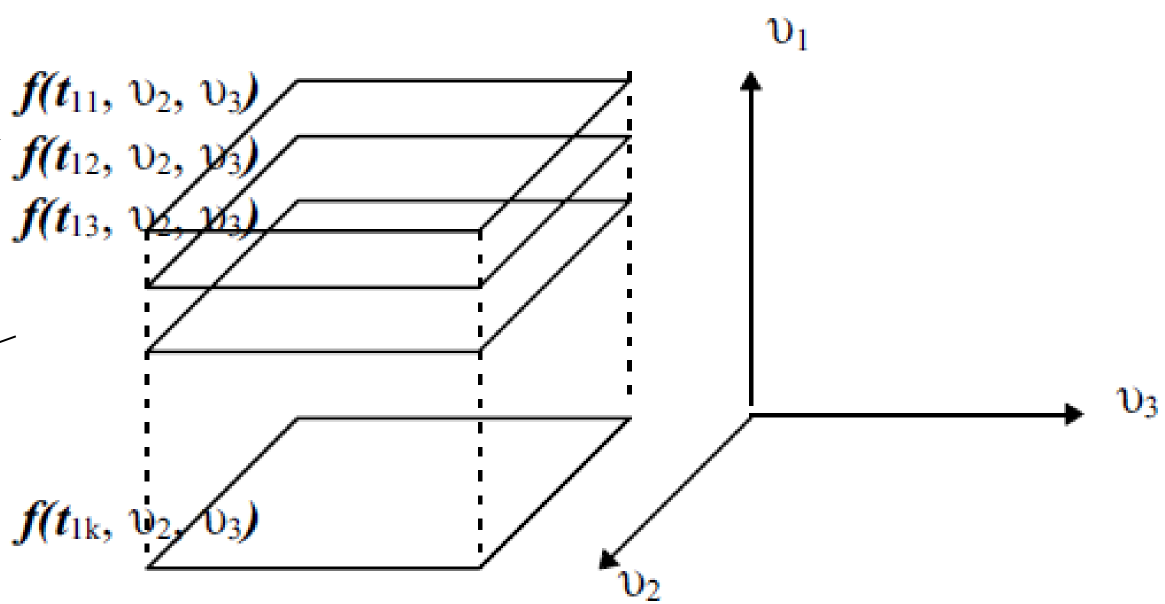
record at this t_1 a “normal” 2D-COSY

↓

$f(t_1, t_2, t_3)$

↓ FT in t_2 and t_3

$f(t_1, \nu_2, \nu_3)$



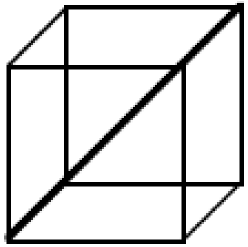
FT in t_1

$f(\nu_1, \nu_2, \nu_3)$

The $f(\nu_1,\nu_2,\nu_3)$ spectrum (e.g. AMX spin system)

1. Diagonal peaks [e.g. $\Omega_A(\nu_1)$, $\Omega_A(\nu_2)$, $\Omega_A(\nu_3)$] along the body diagonal:
from lower left-hand
to upper right-hand

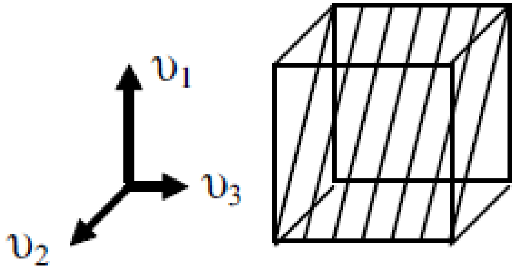
Comment: unmigrated magnetisation during t_1, t_2 as well as t_3
Analogue: normal 2D-COSY diagonal



2. Cross-diagonal peaks along the cross-diagonal planes:

e.g. $\Omega_A(\nu_1)$, $\Omega_A(\nu_2)$, $\Omega_M(\nu_3)$ $\nu_1=\nu_2$

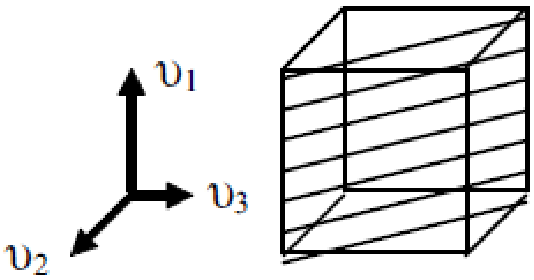
Comment: unmigrated magnetisation during the pulse separating t_1 and t_2
than coherence is transferred during the pulse separating t_2 and t_3
Analogue: normal 2D-COSY



e.g. $\Omega_A(\nu_1)$, $\Omega_M(\nu_2)$, $\Omega_M(\nu_3)$ $\nu_2=\nu_3$

Comment: coherence is transferred during the pulse separating t_1 and t_2 than coherence is untransferred during the pulse separating t_2 and t_3

Analogue: normal 2D-COSY

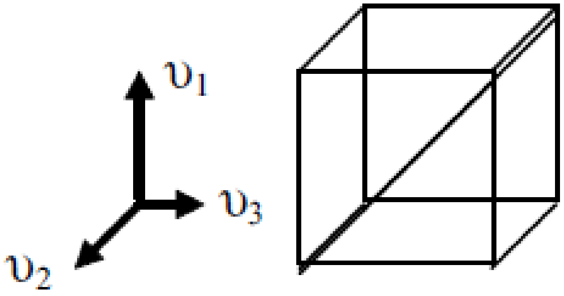


3. Back transfer peaks along the back transfer plane:

e.g. $\Omega_A(\nu_1)$, $\Omega_M(\nu_2)$, $\Omega_A(\nu_3)$ $\nu_1=\nu_3$

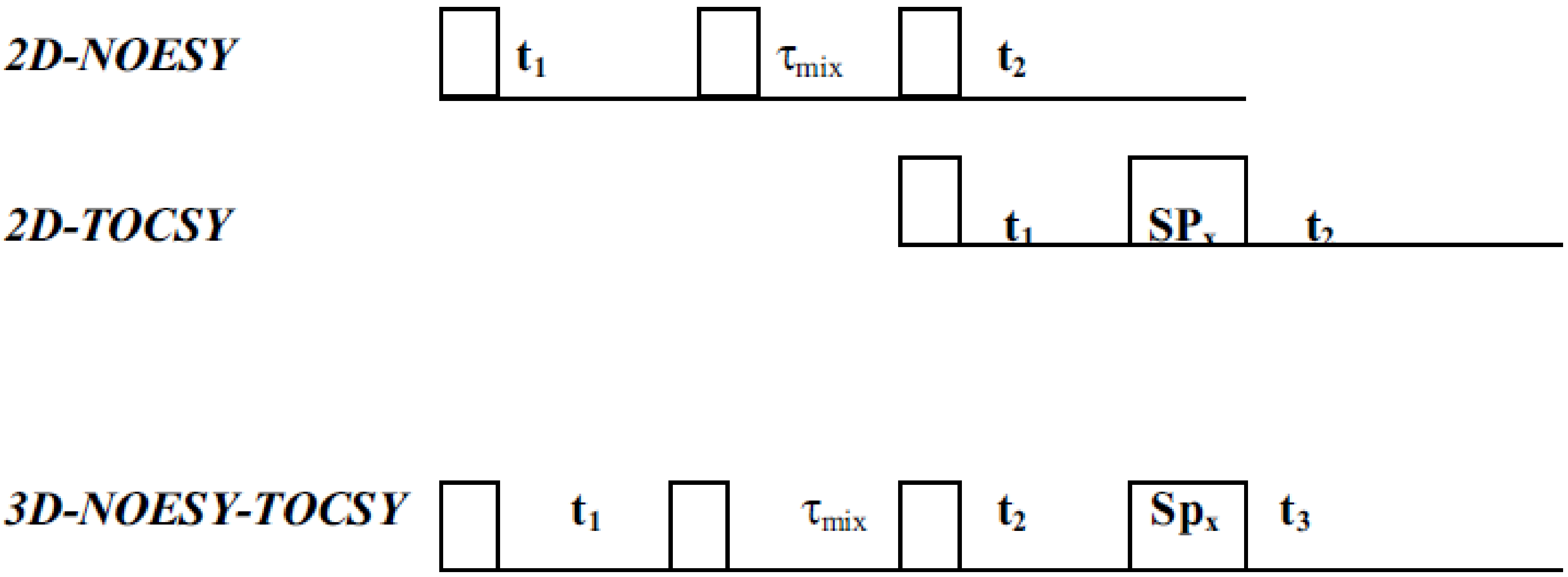
Comment: coherence is transferred during the pulse separating t_1 and t_2 than coherence is back transferred during the pulse separating t_2 and t_3

Analogue: none



3D NOESY-TOCSY

Combining two *convenient* 2D experiments (e.g. 2D-NOESY and a 2D-TOCSY)



explanation: record at a fix t_1 a “normal” 2D-TOCSY where -the acquisition dim is t_3

-the freq. lab. period is t_2

↓

increase t_1 ←

↓ $t_1 + n$ (dw) n=1,2,…k (e.g. k=32)

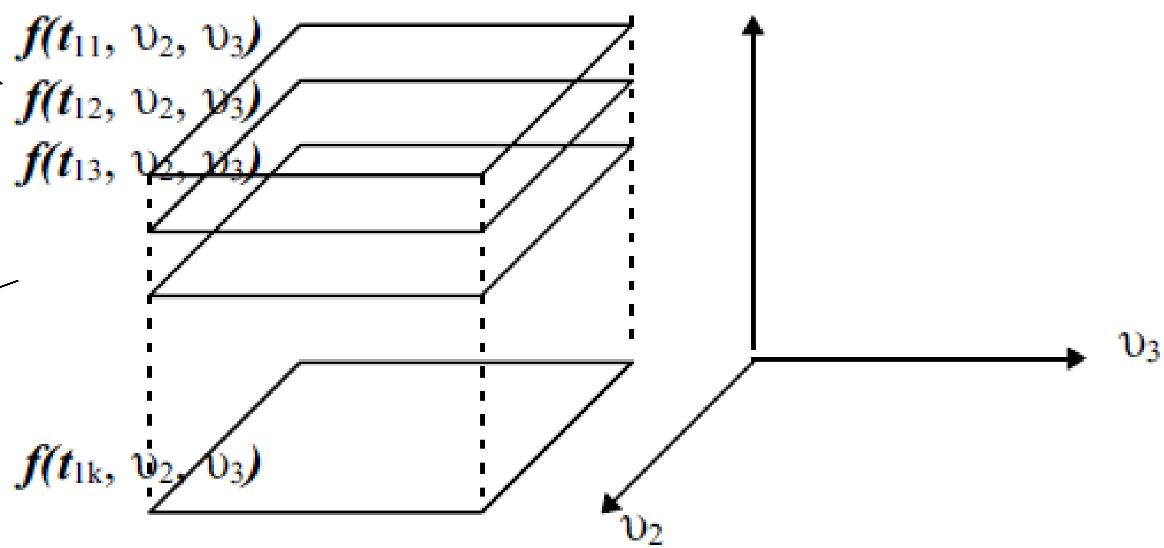
record at this t_1 a “normal” 2D-TOCSY

↓

$f(t_1, t_2, t_3)$

↓ FT in t_2 and t_3

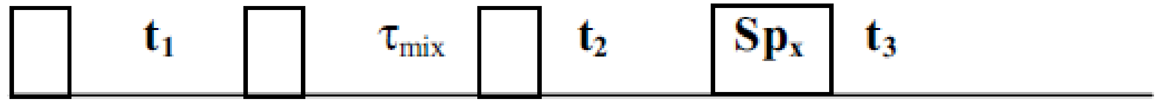
$f(t_1, \nu_2, \nu_3)$



FT in t_1

$f(\nu_1, \nu_2, \nu_3)$

3D-NOESY-TOCSY

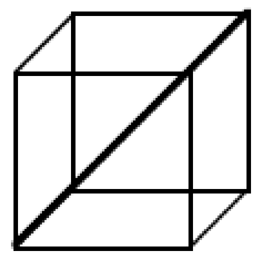


F_1 -- *NOE* --> F_2 -- *TOCSY* --> F_3

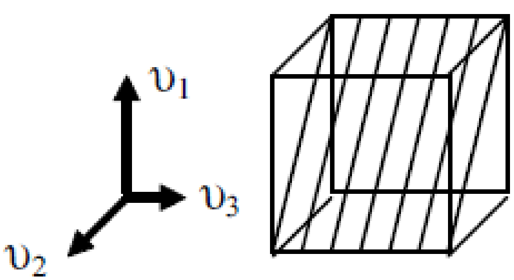
The $f(\nu_1, \nu_2, \nu_3)$ spectrum (e.g. AMX spin system)

1. Diagonal peaks [e.g. $\Omega_A(\nu_1), \Omega_A(\nu_2), \Omega_A(\nu_3)$] along the body diagonal:
from lower left-hand
to upper right-hand

Comment: unmigrated magnetisation during t_1, t_2 as well as t_3
Analogue: normal 2D diagonal



2. Cross-diagonal peaks along the cross-diagonal planes:



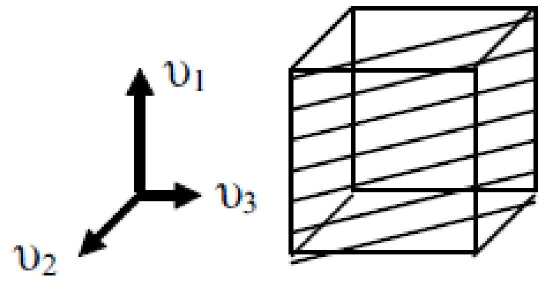
e.g. $\Omega_A(\nu_1), \Omega_A(\nu_2), \Omega_M(\nu_3)$ $\nu_1 = \nu_2$

Comment: unmigrated magnetisation during the pulse separating t_1 and t_2
than coherence is transferred during the pulse separating t_2 and t_3
Analogue: normal 2D-TOCSY

e.g. $\Omega_A(\nu_1)$, $\Omega_M(\nu_2)$, $\Omega_M(\nu_3)$ $\nu_2=\nu_3$

Comment: coherence is transferred during the pulse separating t_1 and t_2
than coherence is untransferred during the pulse separating t_2 and t_3

Analogue: normal 2D-TOCSY

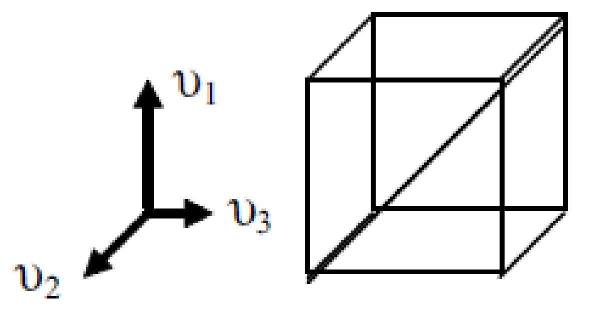


3. Back transfer peaks along the back transfer plane:

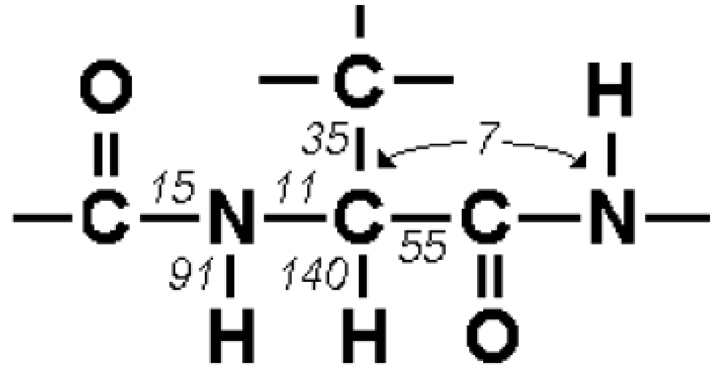
e.g. $\Omega_A(\nu_1)$, $\Omega_M(\nu_2)$, $\Omega_A(\nu_3)$ $\nu_1=\nu_3$

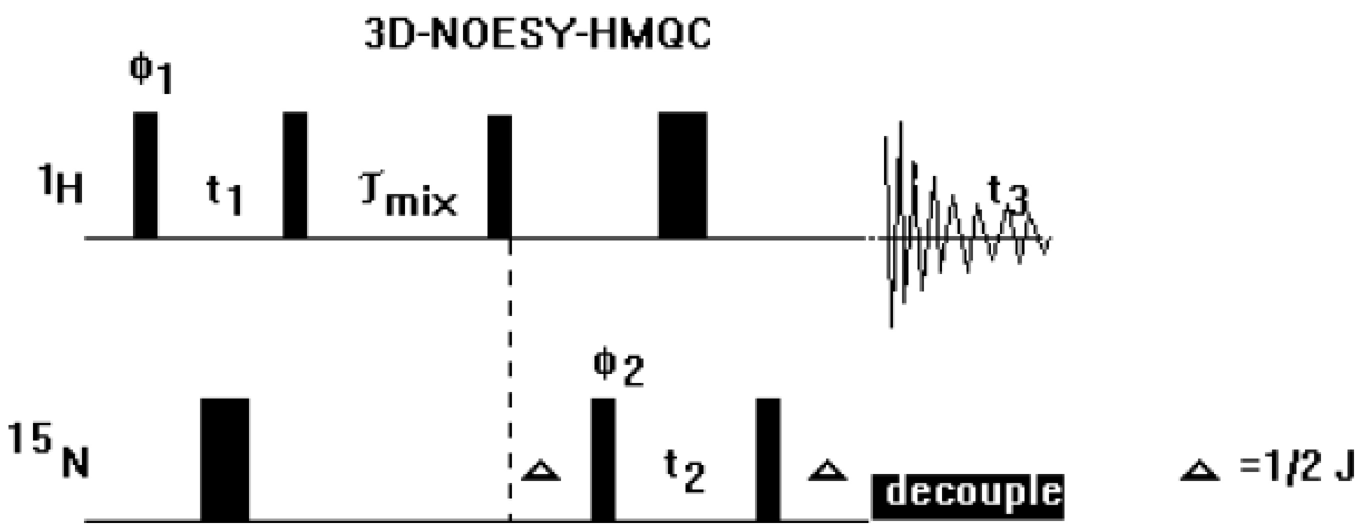
Comment: coherence is transferred during the pulse separating t_1 and t_2
than coherence is back transferred during the pulse separating t_2 and t_3

Analogue: none



Heteronuclear 3D NMR





1. The first 90° => transverse magnetisation
2. This is frequency labelled during t_1
3. The second 90° => longitudinal magnetisation
4. During the mixing time => longitudinal magnetisation is transferred via cross-relaxation
5. The third 90° => transverse magnetisation *(end of NOESY part)*

H_z^A --90^{oH}--> H_y^A --t_1--> $H_y^A(\Omega_A t_1)$ --90^{oH}--> $H_z^A(\Omega_A t_1)$ --NOE--> $H_z^B(\Omega_A t_1)$--90^{oH}--> $H_y^B(\Omega_A t_1)$

6. During the Δ time => anti phase coherence is created (Δ_{ideal} = 1/(2*91 Hz) ≈ 5 ms)
7. The fourth 90° (first 90° on N) => generates multiple quantum coherence
8. This is frequency labelled during t_2
9. The fifth 90° (second 90° on N) => generates from multiple quantum coherence anti phase coherence
10. During the second Δ => anti phase coherence is refocused to in-phase ^{1}H magnetisation
11. Detected during t_3 *(end of HMQC part)*

$H_y^B(\Omega_A t_1)$ --Δ--> $H_x^B N_z(\Omega_A t_1)$ --90^{oN}--> $H_x^B N_y(\Omega_A t_1)$ --t_2--> $H_x^B N_y(\Omega_A t_1)(\Omega_N t_2)$ --90^{oN}--> $H_x^B N_z(\Omega_A t_1)(\Omega_N t_2)$ --Δ--> $H_y^B(\Omega_A t_1)(\Omega_N t_2)$--$t_3$--> $H_y^B(\Omega_A t_1)(\Omega_N t_2)(\Omega_B t_3)$

Summary:

H_z^A -- 3D NOESY-HMQC --> $H_y^B(\Omega_A t_1)(\Omega_N t_2)(\Omega_B t_3)$