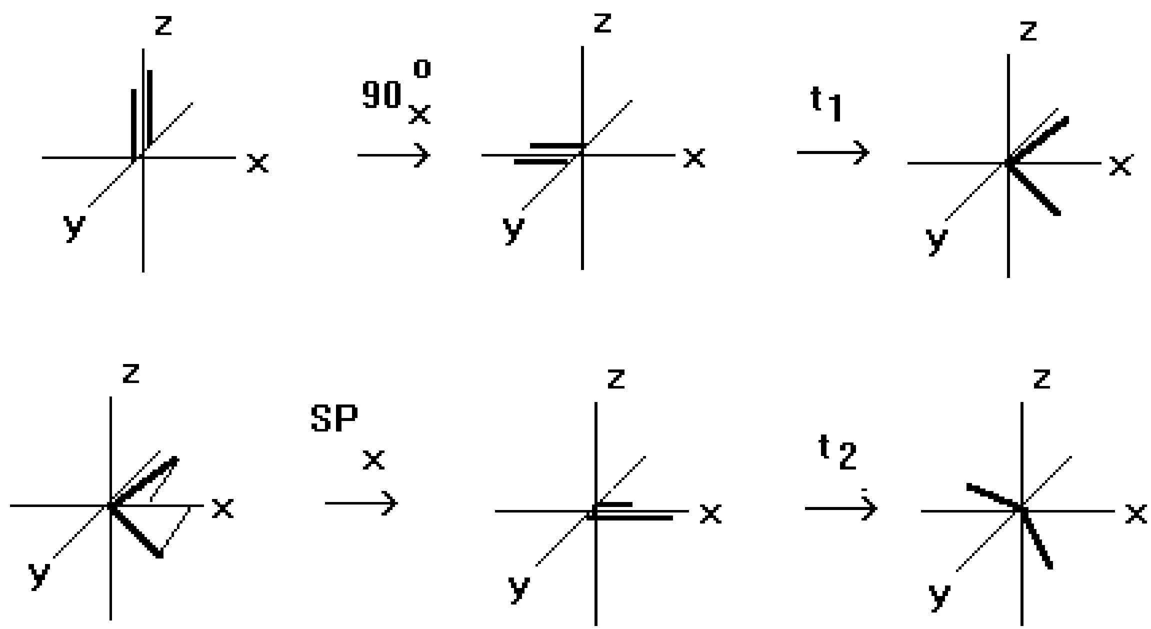
TOCSY =TOtal-Correlated SpectroscopY

The pulse sequence: $90°_x$ - t_1 - $(\text{spin lock})_x$ - t_2

Consider: Ω_I, Ω_S and J_{IS}



σ[eq.] **I_z and S_z**

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

σ[0] **$-I_y$ and $-S_y$**

$\hat{H} = \hat{I}_z(\Omega_I t_1) + \check{S}_z(\Omega_S t_1)$ $\downarrow \ t_1$

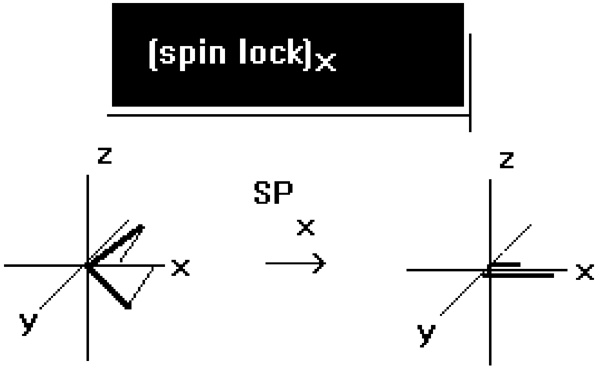
$$-\mathbf{I}_y \cos(\Omega_I t_1)$$
$$+\mathbf{I}_x \sin(\Omega_I t_1)$$
$$-\mathbf{S}_y \cos(\Omega_S t_1)$$
$$+\mathbf{S}_x \sin(\Omega_S t_1)$$

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

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

$\sigma[t_1]$

memo 1: the spin locking field **locks** the magnetization vector **where it is** after t_1. (More precisely **SP_x locks the x component** of the magnetization vector **while other component are decoiled**. Like a gradient, the x component is locked along x and the rest of the coherence is decoiled over time in the y,-z,-y,z plane.) Thus, **it induces equivalence of all spins**.



So **using an x spin lock** from these terms

$$-\mathbf{I}_y \cos(\Omega_I t_1)\cos(\pi J_{IS} t_1) \quad +2\mathbf{I}_x\mathbf{S}_z \cos(\Omega_I t_1)\sin(\pi J_{IS} t_1)$$

$$+\mathrm{I}_x \sin(\Omega_I t_1)\cos(\pi J_{IS} t_1) \quad +2\mathbf{I}_y\mathbf{S}_z \sin(\Omega_I t_1)\sin(\pi J_{IS} t_1)$$

$$-\mathbf{S}_y \cos(\Omega_S t_1)\cos(\pi J_{IS} t_1) \quad +2\mathbf{S}_x\mathbf{I}_z \cos(\Omega_S t_1)\sin(\pi J_{IS} t_1)$$

$$+\mathrm{S}_x \sin(\Omega_S t_1)\cos(\pi J_{IS} t_1) \quad +2\mathbf{S}_y\mathbf{I}_z \sin(\Omega_S t_1)\sin(\pi J_{IS} t_1)$$

only the following **two terms** are not dephased:

$$+\mathbf{I}_x \sin(\Omega_I t_1)\cos(\pi J_{IS} t_1) \quad \text{and} \quad +\mathbf{S}_x \sin(\Omega_S t_1)\cos(\pi J_{IS} t_1).$$

memo 2: the way of how „sum" of prod. op. [($\mathbf{I}_x + \mathbf{S}_x$), ($\mathbf{I}_y - \mathbf{S}_y$) etc.] evolve under spin locking field is as follows:

$$\mathbf{I}_x + \mathbf{S}_x \text{ -------->} \quad \mathbf{I}_x + \mathbf{S}_x$$

$$\mathbf{I}_y + \mathbf{S}_y \text{ -------->} \quad \mathbf{I}_y + \mathbf{S}_y$$

$$\mathbf{I}_z + \mathbf{S}_z \text{ -------->} \quad \mathbf{I}_z + \mathbf{S}_z$$

$$\mathbf{I}_x - \mathbf{S}_x \text{ -------->} \quad (\mathbf{I}_x - \mathbf{S}_x)\cos(2\pi J_{IS}\tau) + (2\mathbf{I}_y\mathbf{S}_z - 2\mathbf{I}_z\mathbf{S}_y)\sin(2\pi J_{IS}\tau)$$

$$\mathbf{I}_y - \mathbf{S}_y \text{ -------->} \quad (\mathbf{I}_y - \mathbf{S}_y)\cos(2\pi J_{IS}\tau) - (2\mathbf{I}_x\mathbf{S}_z - 2\mathbf{I}_z\mathbf{S}_x)\sin(2\pi J_{IS}\tau)$$

$$\mathbf{I}_z - \mathbf{S}_z \text{ -------->} \quad (\mathbf{I}_z - \mathbf{S}_z)\cos(2\pi J_{IS}\tau) + (2\mathbf{I}_x\mathbf{S}_y - 2\mathbf{I}_y\mathbf{S}_x)\sin(2\pi J_{IS}\tau)$$

memo 3: Thus, from ($\mathbf{I}_x + \mathbf{S}_x$) and ($\mathbf{I}_x - \mathbf{S}_x$) terms, $+\mathbf{I}_x$ is derived as:

$$+\mathrm{I}_x = (\mathbf{I}_x + \mathbf{S}_x)1/2 + (\mathbf{I}_x - \mathbf{S}_x)1/2$$

$$= (\mathbf{I}_x + \mathbf{S}_x)1/2 + 1/2\{(\mathbf{I}_x - \mathbf{S}_x)\cos(2\pi J_{IS}\tau) + (2\mathbf{I}_y\mathbf{S}_z - 2\mathbf{I}_z\mathbf{S}_y)\sin(2\pi J_{IS}\tau)\}$$

$$= 1/2\mathbf{I}_x + 1/2\mathbf{S}_x + 1/2\mathbf{I}_x\cos(2\pi J_{IS}\tau) - 1/2\mathbf{S}_x\cos(2\pi J_{IS}\tau) + 1/2(2\mathbf{I}_y\mathbf{S}_z - 2\mathbf{I}_z\mathbf{S}_y)\sin(2\pi J_{IS}\tau)\}$$

and results in the following **3 terms**:

$$= +1/2\mathbf{I}_x(1+\cos(2\pi J_{IS}\tau)) + 1/2\mathbf{S}_x(1-\cos(2\pi J_{IS}\tau)) + 1/2(2\mathbf{I}_y\mathbf{S}_z\text{-}\mathbf{I}_z\mathbf{S}_y)\sin(2\pi J_{IS}\tau)\}$$

memo 3: Thus, $+\mathbf{I}_x$ evolves as 3 terms at the end of SP_x:

$+\mathbf{I}_x$

$$\left\{ \begin{array}{l} +1/2\mathbf{I}_x(1+\cos(2\pi J_{IS}\tau)) \\ +1/2\mathbf{S}_x(1-\cos(2\pi J_{IS}\tau)) \\ +1/2\,(2\mathbf{I}_y\mathbf{S}_z\text{-}2\mathbf{I}_z\mathbf{S}_y)\sin(2\pi J_{IS}\tau)\} \end{array} \right\}$$

In conclusion during an SP_x lock $+I_x$ sin(ΩIt1)cos(πJISt1) and $+S_x$ sin(ΩSt1)cos(πJISt1) **evolves** as follows (6 tems in total):

$$+\mathbf{I}_x \sin(\Omega_I t_1)\cos(\pi J_{IS} t_1) \text{ -----> } \begin{array}{ll} +1/2\mathbf{I}_x & (1+\cos(2\pi J_{IS}\tau))\sin(\Omega_I t_1)\cos(\pi J_{IS} t_1) \\ +1/2\mathbf{S}_x & (1-\cos(2\pi J_{IS}\tau))\sin(\Omega_I t_1)\cos(\pi J_{IS} t_1) \\ \multicolumn{2}{l}{+1/2\,(2\mathbf{I}_y\mathbf{S}_z - 2\mathbf{I}_z\mathbf{S}_y)\sin(2\pi J_{IS}\tau)\sin(\Omega_I t_1)\cos(\pi J_{IS} t_1)} \end{array}$$

and

$$+\mathbf{S}_x \sin(\Omega_S t_1)\cos(\pi J_{IS} t_1) \text{ -----> } \begin{array}{ll} +1/2\mathbf{S}_x & (1+\cos(2\pi J_{IS}\tau))\sin(\Omega_S t_1)\cos(\pi J_{IS} t_1) \\ +1/2\mathbf{I}_x & (1-\cos(2\pi J_{IS}\tau))\sin(\Omega_S t_1)\cos(\pi J_{IS} t_1) \\ \multicolumn{2}{l}{+1/2\,(2\mathbf{S}_y\mathbf{I}_z - 2\mathbf{S}_z\mathbf{I}_y)\sin(2\pi J_{IS}\tau)\sin(\Omega_S t_1)\cos(\pi J_{IS} t_1)} \end{array}$$

memo 4 : $2\mathbf{I}_y\mathbf{S}_z$, $-2\mathbf{I}_z\mathbf{S}_y$, $2\mathbf{S}_y\mathbf{I}_z$ and $-2\mathbf{S}_z\mathbf{I}_y$ terms are all anti-phased coherences.

H <-----> H

a If J_{IS} is small N – C - C - C than

| |

the anti-phased spectrum (--------) looks like this: (---------) . The signal vanishes

| |

H<->H

b If J_{IS} is not small - N - C - than we observe *COSY*- type cross-peaks.

memo 6 : Notice, that at a given τ, the $1+\cos(2\pi J_{IS}\tau)$ term can be zero, if $\cos(2\pi J_{IS}\tau) = -1$. So the off-diagonal peaks can disappear.

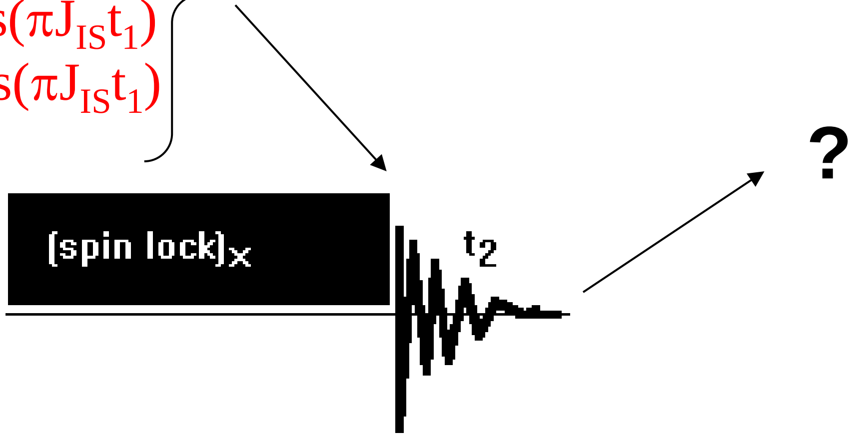
So in an ideal situation the following 4 terms evolve during ACQ:

$$1/2\mathbf{I}_x(1+\cos(2\pi J_{IS}\tau))\sin(\Omega_I t_1)\cos(\pi J_{IS} t_1)$$
$$1/2\mathbf{S}_x(1-\cos(2\pi J_{IS}\tau))\sin(\Omega_I t_1)\cos(\pi J_{IS} t_1)$$
$$1/2\mathbf{S}_x(1+\cos(2\pi J_{IS}\tau))\sin(\Omega_S t_1)\cos(\pi J_{IS} t_1)$$
$$1/2\mathbf{I}_x(1-\cos(2\pi J_{IS}\tau))\sin(\Omega_S t_1)\cos(\pi J_{IS} t_1)$$

$$\beta_d := 1/2(1+\cos(2\pi J_{IS}\tau))$$
$$\beta_{od} := 1/2(1-\cos(2\pi J_{IS}\tau))$$

By incorporating β_d and β_{od}, the four terms before **ACQ** are as follows:

$$\left\{ \begin{array}{l} \mathbf{I}_x \beta_d \sin(\Omega_I t_1)\cos(\pi J_{IS} t_1) \\ \mathbf{S}_x \beta_{od} \sin(\Omega_I t_1)\cos(\pi J_{IS} t_1) \\ \mathbf{S}_x \beta_d \sin(\Omega_S t_1)\cos(\pi J_{IS} t_1) \\ \mathbf{I}_x \beta_{od} \sin(\Omega_S t_1)\cos(\pi J_{IS} t_1) \end{array} \right\}$$



the diagonal $\mathbf{I}_x$ term during ACQ $\Rightarrow$

$$+\mathbf{I}_x \beta_d \sin(\Omega_I t_1)\cos(\pi J_{IS} t_1)\cos(\Omega_I t_2)\cos(\pi J_{IS} t_2)$$
$$+2\mathbf{I}_y\mathbf{S}_z\beta_d \sin(\Omega_I t_1)\cos(\pi J_{IS} t_1)\cos(\Omega_I t_2)\sin(\pi J_{IS} t_2)$$
$$+\mathbf{I}_y \beta_d \sin(\Omega_I t_1)\cos(\pi J_{IS} t_1)\sin(\Omega_I t_2)\cos(\pi J_{IS} t_2)$$
$$-2\mathbf{I}_x\mathbf{S}_z\beta_d \sin(\Omega_I t_1)\cos(\pi J_{IS} t_1)\sin(\Omega_I t_2)\sin(\pi J_{IS} t_2)$$

the diagonal $\mathbf{S}_x$ term during ACQ $\Rightarrow$

$$+\mathbf{S}_x \beta_d \sin(\Omega_S t_1)\cos(\pi J_{IS} t_1)\cos(\Omega_S t_2)\cos(\pi J_{IS} t_2)$$
$$+2\mathbf{I}_z\mathbf{S}_y\beta_d \sin(\Omega_S t_1)\cos(\pi J_{IS} t_1)\cos(\Omega_S t_2)\sin(\pi J_{IS} t_2)$$
$$+\mathbf{S}_y \beta_d \sin(\Omega_S t_1)\cos(\pi J_{IS} t_1)\sin(\Omega_S t_2)\cos(\pi J_{IS} t_2)$$
$$-2\mathbf{I}_z\mathbf{S}_x\beta_d \sin(\Omega_S t_1)\cos(\pi J_{IS} t_1)\sin(\Omega_S t_2)\sin(\pi J_{IS} t_2)$$

off-diagonal $\mathbf{I}_x$ term during ACQ $\Rightarrow$

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

off-diagonal $\mathbf{S}_x$ term during ACQ $\Rightarrow$

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

memo 1: receiver on x

therefore only the four x term remain

$$-\mathbf{I}_x\,\beta_d\,\sin(\Omega_I t_1)\cos(\pi J_{IS} t_1)\cos(\Omega_I t_2)\cos(\pi J_{IS} t_2)$$
$$+\mathbf{S}_x\,\beta_d\,\sin(\Omega_S t_1)\cos(\pi J_{IS} t_1)\cos(\Omega_S t_2)\cos(\pi J_{IS} t_2)$$
$$+\mathbf{I}_x\,\beta_{od}\,\sin(\Omega_S t_1)\cos(\pi J_{IS} t_1)\cos(\Omega_I t_2)\cos(\pi J_{IS} t_2)$$
$$+\mathbf{S}_x\,\beta_{od}\,\sin(\Omega_I t_1)\cos(\pi J_{IS} t_1)\cos(\Omega_S t_2)\cos(\pi J_{IS} t_2)$$

memo 2: $\sin(A)\cos(B) = 1/2[\sin(A+B)+\sin(A-B)]$

$\cos(A)\cos(B) = 1/2[\cos(A+B)+\cos(A-B)]$

therefore

$$+1/4\mathbf{I}_x\beta_d\,[+\sin\{(\Omega_I+\pi J_{IS})t_1\}+\sin\{(\Omega_I-\pi J_{IS})t_1\}][+\cos\{(\Omega_I+\pi J_{IS})t_2\}+\cos\{(\Omega_I-\pi J_{IS})t_2\}]$$
$$+1/4\mathbf{S}_x\beta_d\,[+\sin\{(\Omega_S+\pi J_{IS})t_1\}+\sin\{(\Omega_S-\pi J_{IS})t_1\}][+\cos\{(\Omega_S+\pi J_{IS})t_2\}+\cos\{(\Omega_S-\pi J_{IS})t_2\}]$$
$$+1/4\mathbf{I}_x\beta_{od}\,[+\sin\{(\Omega_S+\pi J_{IS})t_1\}+\sin\{(\Omega_S-\pi J_{IS})t_1\}][+\cos\{(\Omega_I+\pi J_{IS})t_2\}+\cos\{(\Omega_I-\pi J_{IS})t_2\}]$$
$$+1/4\mathbf{S}_x\beta_{od}\,[+\sin\{(\Omega_I+\pi J_{IS})t_1\}+\sin\{(\Omega_I-\pi J_{IS})t_1\}][+\cos\{(\Omega_S+\pi J_{IS})t_2\}+\cos\{(\Omega_S-\pi J_{IS})t_2\}]$$

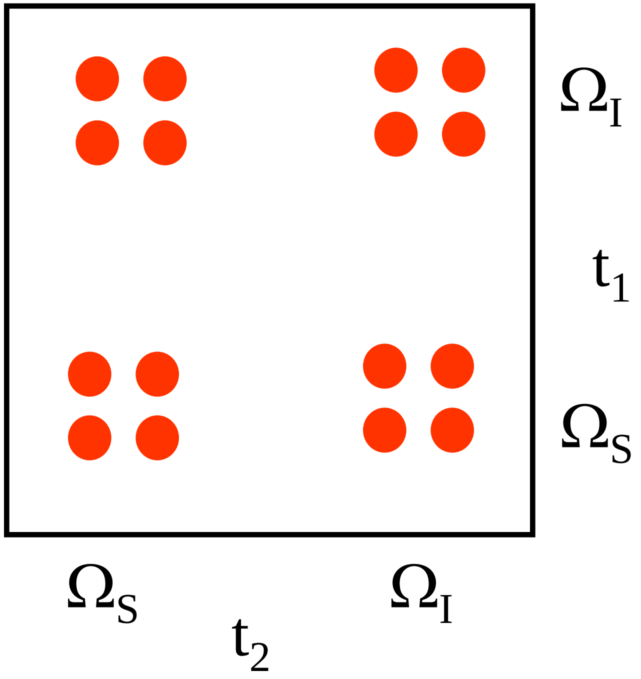
the following terms can be found

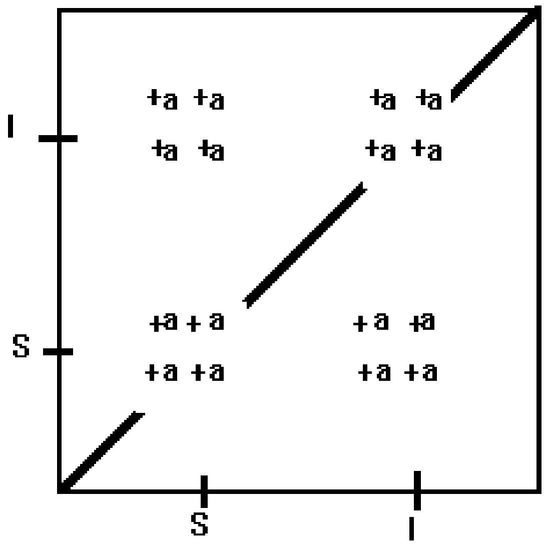
$\mathbf{I}_x$ [+ .. + .. + .. + ..] at Ω_I , Ω_I
$\mathbf{I}_x$ [+ .. + .. + .. + ..] at Ω_S , Ω_I
$\mathbf{S}_x$ [+ .. + .. + .. + ..] at Ω_S , Ω_S
$\mathbf{S}_x$ [+ .. + .. + .. + ..] at Ω_I , Ω_S

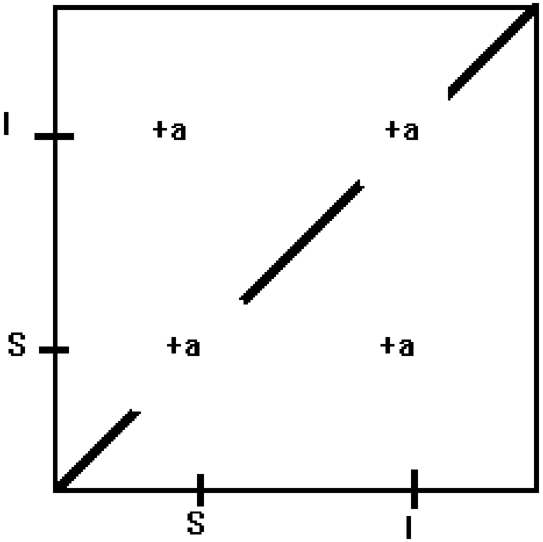
if one sets the phase that *sin is absorptive (a) in t_1, cos is absorptive (a) in t_2*

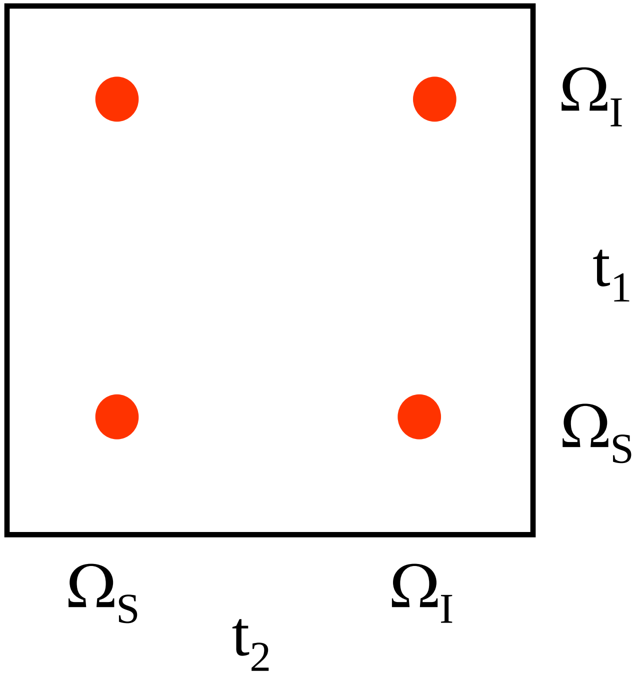
$\mathbf{I}_x\ \beta_d$ [+a .. +a .. +a .. +a ..] at Ω_I , Ω_I
$\mathbf{I}_x\ \beta_{od}$ [+a .. +a .. +a ..+a ..] at Ω_S , Ω_I
$\mathbf{S}_x\ \beta_d$ [+a .. +a .. +a .. +a ..] at Ω_S , Ω_S
$\mathbf{S}_x\ \beta_{od}$ [+a .. +a .. +a .. +a ..] at Ω_I , Ω_S

Since $J_{IS} = 0$ (through bond coupling negligible) than









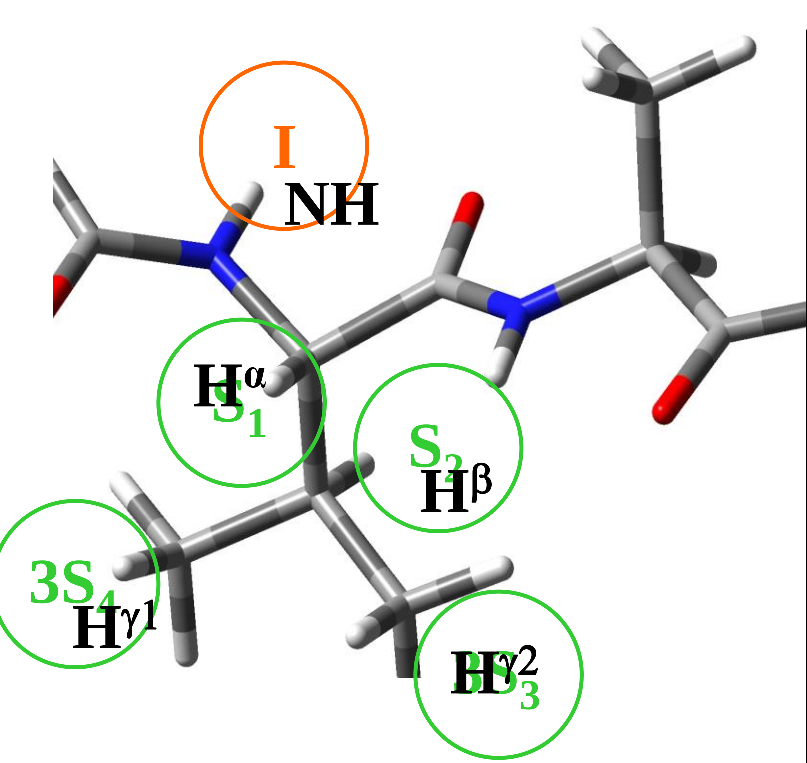
$\beta_d := 1/2(1+\cos(2\pi J_{IS}\tau))$
$\beta_{od} := 1/2(1-\cos(2\pi J_{IS}\tau))$

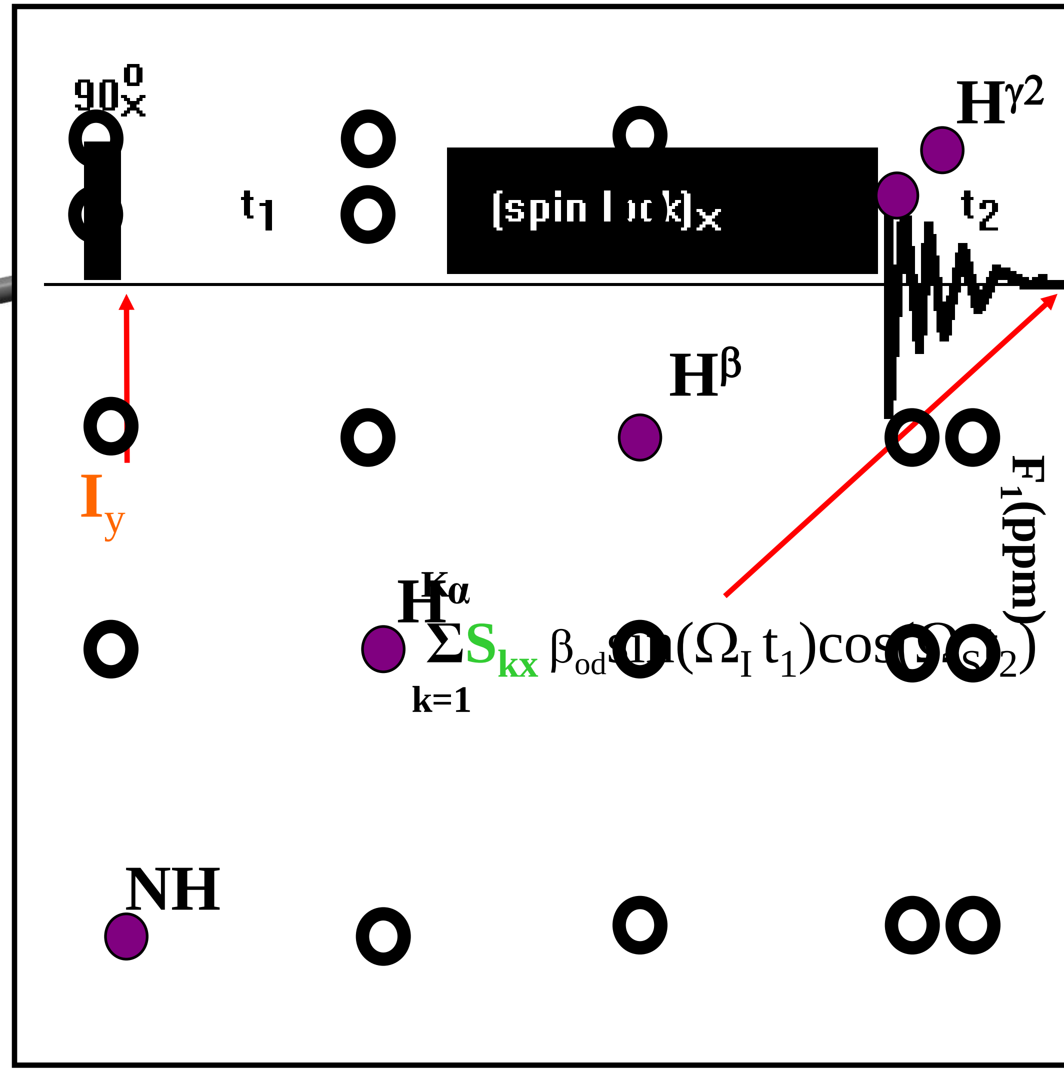
Both the diagonals and the off-diagonals have absorptive line shape and they all can be positive. If $\cos(2\pi J_{IS}\tau)=0$ [$\tau = 1/(4J_{IS})$] diagonal and off diagonal have the same intensity.
In general : $1 \leq \beta_d \leq 0$ and $+1/2 \leq \beta_d \leq -1/2$
Depending on the length of the spin lock the off-diagonal TOCSY peaks **are positive or negative.**
TOCSY peaks have similar intensity than DQF-COSY and are less intensive than COSY.

spinrendszerek azonosítása

^1H-^1H TOCSY

protonok teljes korrelációját létrehozó spektrum





$$\sum_{k=1} S_{kx}\ \beta_{od} \sin(\Omega_I t_1)\cos(\Omega_S t_2)$$

diagonális jelek

diagonálison kívüli jelek

F_2(ppm)

β_{od} = diagonálison kívüli intenzitások

A spektrumban a J_{IS} okozta modulációtól eltekintünk

The ^{1}H-^{1}H TOCSY spectrum of a folded peptide: