COHERENCE SELECTION

Steps in NMR experiments:

1. Coherence generation
2. Coherence transfer and/or mixing
   - through-bond coherence transfer
     - COSY-type
     - TOCSY
   - through-space magnetisation transfer
   - heteronuclear coherence transfer
3. Coherence selection
   - via phase cycling
   - via pulsed field gradient
4. Acquisition

COHERENCE SELECTION

ultimate goal: to generate the wanted observable
achieved by : the evolution of the density operator in time
the problem: via multiple pulses and delays we produce several different coherences among them some are wanted some aren't
the solution: one has to select the desired, and only the desired coherence transfer pathway
the answer:
- phase cycling
  - action : repeating the pulse sequence several times but varying the relative phase of selected pulses
  - selection: co-adding the signals
- pulsed field gradient
  - action: activation of a field gradient at selected points in the pulse sequence
  - selection: *in situe*

COHERENCE-LEVELS

memo. 1.: in coherence level diagram the relaxation is ignored (as in POF)

memo. 2.: two spin system -> possible spin states : αα
αβ
βα
ββ

single-quantum coherence	$\Delta m = \pm 1$	one spin state is changing	e.g. αα->αβ
double-quantum coherence	$\Delta m = \pm 2$	two spin states are changing	e.g. αα-> ββ
zero-quantum coherence	$\Delta m = 0$	two spins states are changing but the spins flip in opposite sense	e.g. βα->αβ

memo 3.: longitudinal (z) magnetisation was a zero-quantum coherence

p = Δm is the order of the coherence

property : abs (p) ≤ number of spins (e.g. I and S $-2 \leq p \leq +2$)

zero-quantum coherence and z-magnetisation have coherence level	0
single-quantum coherence has coherence level	±1
double-quantum coherence has coherence level	±2

the density operator , σ, is : $\sigma = \sum_{i=-p_{max}}^{p_{max}} \sigma_i$

where σ_i is the component of the overall density op. associated with the i-th coherence level. (p_{max} is the maximum possible coh. level e.g. for a three spin system, AMX, $p_{max} = 3$)

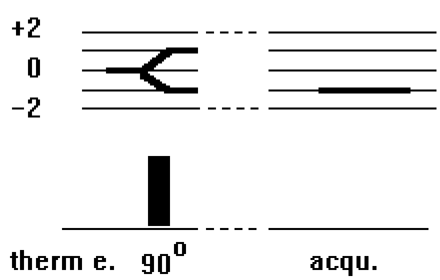
memo. 4.: a real spin system such as Leu (A_3B_3MPTX) has 2p+1 -> 21 possible coh. levels.

rules : 1. rf. pulses can induce the coherence to be transferred from one level into another (from a given level [if this is not the thermal equ.] into all other available levels)

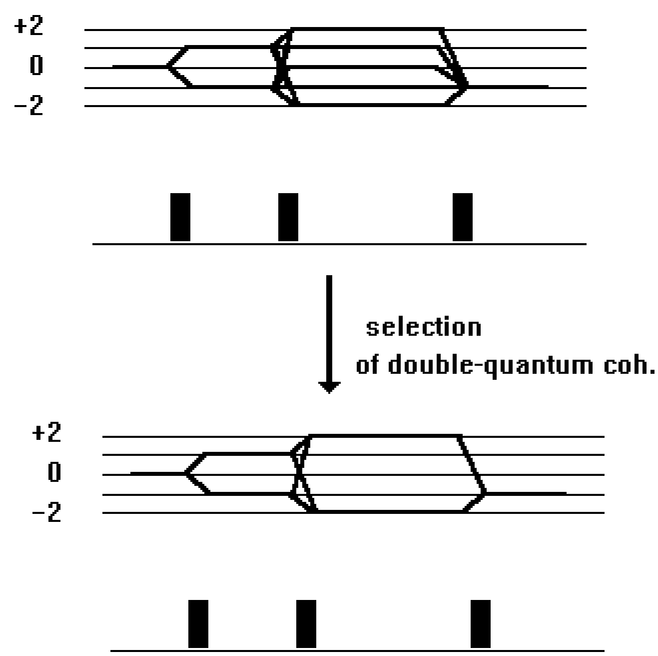
2. free-precession conserves the coherence-order.

practical notations for complex signal quadrature detection:

- coherence transfer pathway starts at p = 0 and ends at p = -1
- from thermal equ. (effect of the first pulse) coherence order ±1 is created only



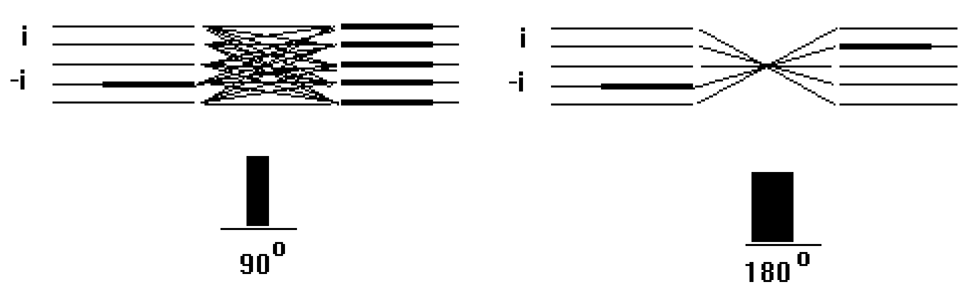
COHERENCE SELECTION



Only the double-quant coherence are to be retained and the pathways of coh. level +1, 0, -1 during the second delay should be discarded.

comment 1.: a $90^{o} \pm k\pi$ (k = 0,1,2,...) pulse produces from any coherence order all possible coherence orders {from coh. order i -> p, (p-1), ...,0,...-(p-1), -p and $-p \leq i \leq +p$}

comment 2.: a $180^{o} \pm k\pi$ (k = 0,1,2,...) pulse produces from coherence order i -> only -i {from coh. order i -> -i where $-p \leq i \leq +p$}

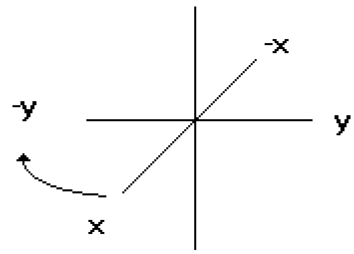


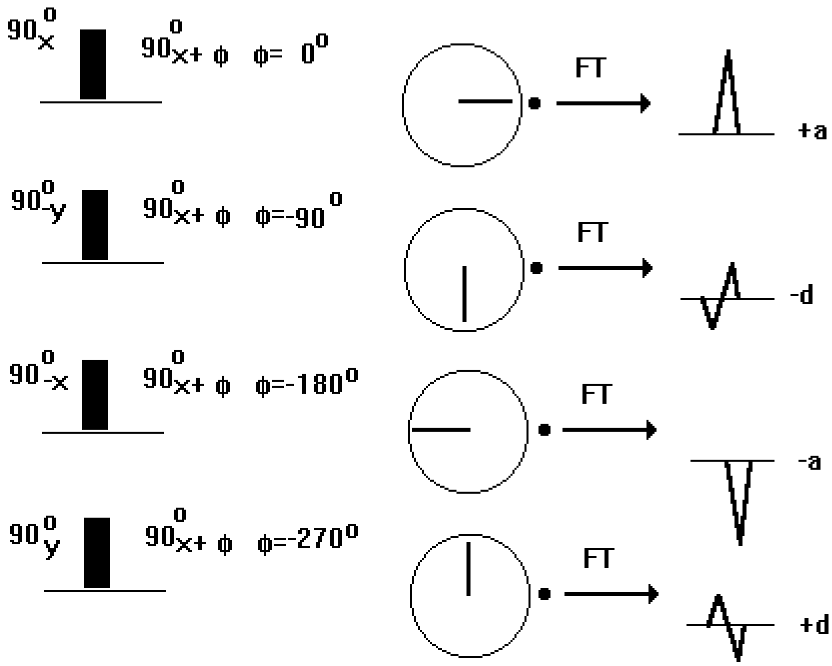
COHERENCE SELECTION via PHASE CYCLING:

Transverse magnetisation (single-quant. coh. between two nuclear angular-momentum states) induces voltage in the detection coil. The detected signal oscillates in time.

Lets consider the vector model.

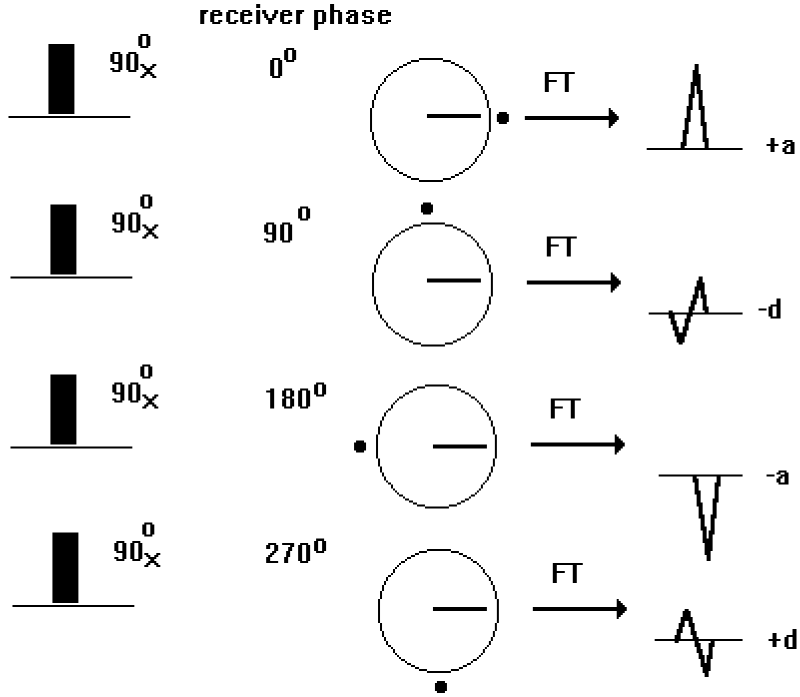
The phase is the relative position of this vector at $t_{acqu.}=0$.



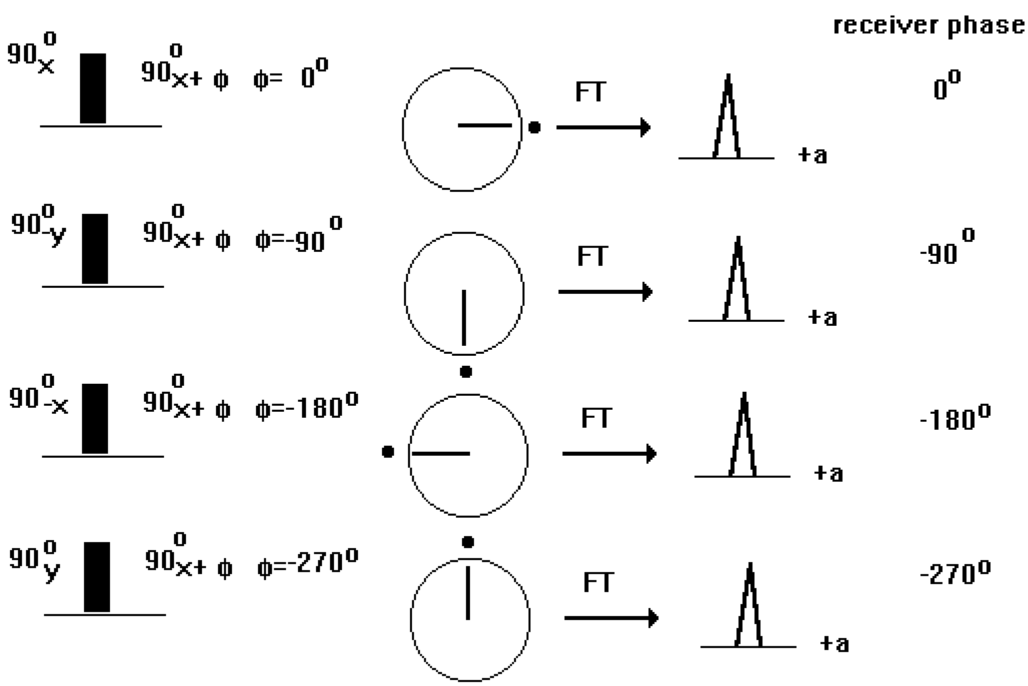


Receiver phase constant, and the phase of the 90^o_x is incremented by -90^o.

comment : adding the signals of the four experiments no spectrum is resulted in.



Receiver phase is incremented by 90^o , and the phase of the 90^o is a constant x.
comment : adding the signals of the four experiments no spectrum is resulted in.



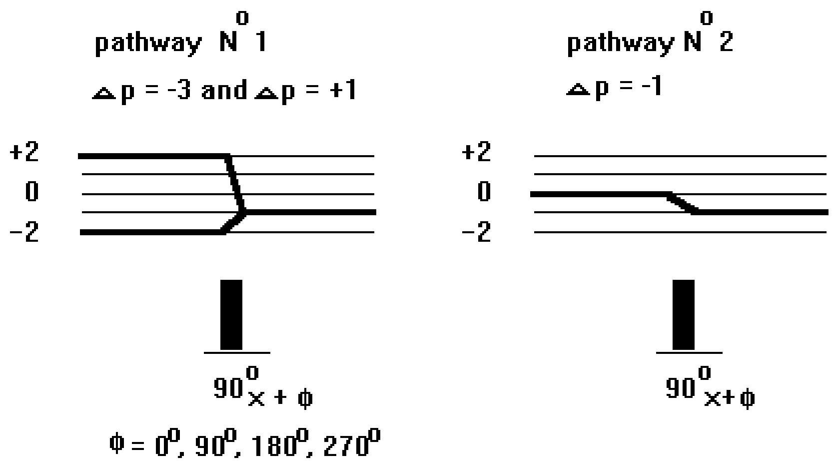
Both the receiver phase and the phase of the 90^o_x are incremented by -90^o .
comment: adding the signals of the four experiments: "+a spectrum" obtained with intensity 4

who to select the coherence transfer path?

Due to a pulse coherence order changes for i to k : $\Delta p = i - k$.
If the phase of this pulse is changed by ϕ, then the acquired phase shift is $-\Delta p\phi$

e.g. if i= +1 and k = +3 than change in coh. order (Δp) is +1 - (+3) = -2
and the acquired phase shift is $-(-2)\ \phi = +2\phi$

who to select between the two following pathways



Pulse phase (ϕ)	Δp (-1- [p])	$-\Delta p\ \phi$	equi. cycle ($0^o \leq ... \leq 360^o$)	rec. phase set to	spectrum
double qunat. coh. p = +2					
0	-3	0	0	0	+a
90	-3	270	270	270	+a
180	-3	540	180	180	+a
270	-3	810	90	90	+a
double qunat. coh. p = -2					
0	+1	0	0	0	+a
90	+1	-90	270	270	+a
180	+1	-180	180	180	+a
270	+1	-270	90	90	+a
zero qunat. coh. p = 0					
0	-1	0	0	0	+a
90	-1	90	90	270	-a
180	-1	180	180	180	+a
270	-1	270	270	90	-a

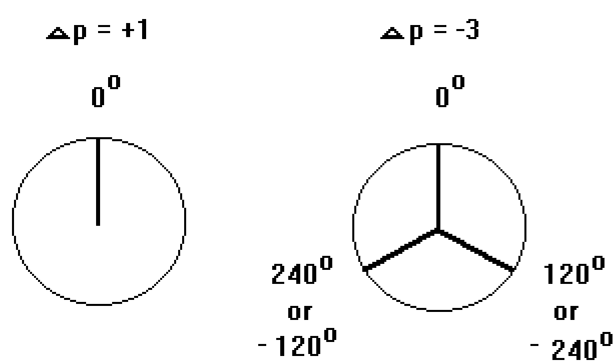
After the four steps p = +2 and p = -2 result in 4*(+a), but with the **same** receiver phase co-adding the four spectra of p = 0 the result: 2*(+a) + 2*(-a) = 0

The *Bodenhausen* representation is based on which Δp do pass and which don't.
{Here Δp = -3 and +1 passed: so **-3** (-2) (-1) (0) **+1** (+2) (+3)}

comment 1.:
In an N step phase cycle (the value of $360^o/N$ is incremented), with the Δp pathway also Δm pathways are selected, where Δm = Δp ± kN (k = 1,2,3,..)
{e.g. N =4 [90^o increments] and Δp = -3 then Δm = -3 ± k4 (k = 1,2,3,..)
so Δm = **...., -7, -3, +1, +5, +9, ...**}
comment 2.: the selection of Δp among r possible values requires at least an r step phase cycling.

Pulse phase (ϕ)	Δp (-1- [p])	-Δp ϕ	equi. cycle (0^o≤...≤360^o)	rec. phase set to	spectrum
double qunat. coh. p = +2					
0	-3	0	0	0	+a
60	-3	180	180	300	+120 d
120	-3	360	0	240	+240 d
180	-3	540	180	180	+a
240	-3	720	0	120	+120 d
300	-3	900	180	60	-120d (or 240d)
double qunat. coh. p = -2					
0	+1	0	0	0	+a
60	+1	-60	300	300	+a
120	+1	-120	240	240	+a
180	+1	-180	180	180	+a
240	+1	-240	120	120	+a
300	+1	-300	60	60	+a

J. Keeler type vector diagram for the above:



After the six steps $\Delta p = +1$ result is 6*(+a).
But with the **same** receiver phase co-adding the six spectra of $\Delta p = -3$ the result is 0.
(The result of the six vectors are 0.)

So with the present phase cycle we have retained $\Delta p = +1$ and eliminated $\Delta p = -3$.
(In fact we have retained $\Delta m = +1 \pm k6$ (k = 1,2,3,..), so **-5, +1, +7** etc. are retained .)

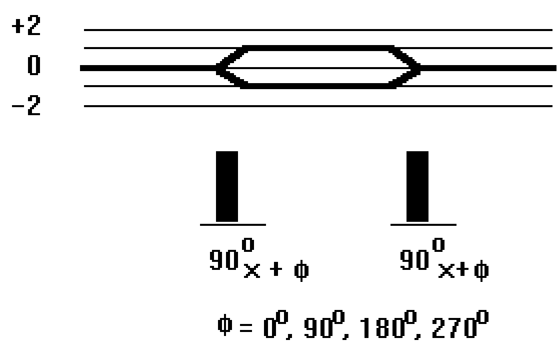
Practical aspects:

In theory - **each pulse** must have a specific phase cycle
- **each phase cycle** are to be executed independently.

In practice appropriate pulses and delays are grouped and considered to be phase cycled **together**.

In reality : - the first 90^o is not phase cycled (it produces only $\Delta p = \pm 1$)
- the last pulse is not phase cycled (only p = -1 is observed)
for spin 1/2 N coupled spins are required to produce N-quant. coh.
- phase cycling against coh. order > N is unnecessary
(for proton -5 < coh. ord. <+5 is to be considered only.)

e.g.



aim : to select only the overall pathway $\Delta p = 0$.
ideally: independent 4 step phase cycle for the first and for the second pulse -> a total of 16 steps are required.
grouping: grouping the two 90^o s and the intervening delay into one, a 4 step phase cycle may provide enough selectivity.

Pulse phase (ϕ)	Δp	$-\Delta p\ \phi$	equi. cycle ($0^o \leq ... \leq 360^o$)	rec. phase kept on	spectrum
0	0	0	0	0	+a
90	0	0	0	0	+a
180	0	0	0	0	+a
270	0	0	0	0	+a

We have retained $\Delta m = +0 \pm k4$ (k = 1,2,3,..), so **-8, -4, 0, +4, +8** etc.

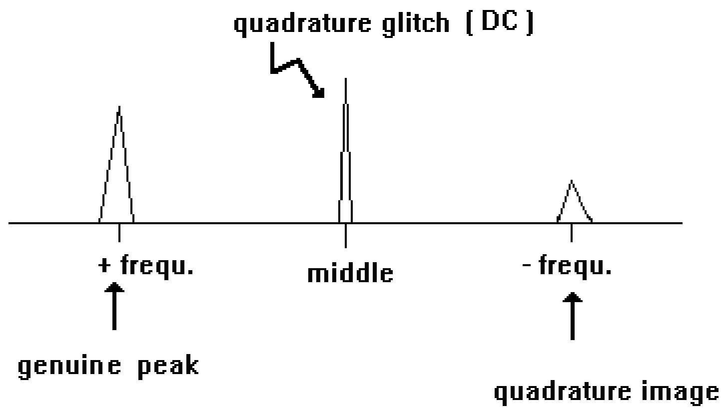
Artifact suppression via phase cycling:

CYCLOPS: compensate quadrature immages

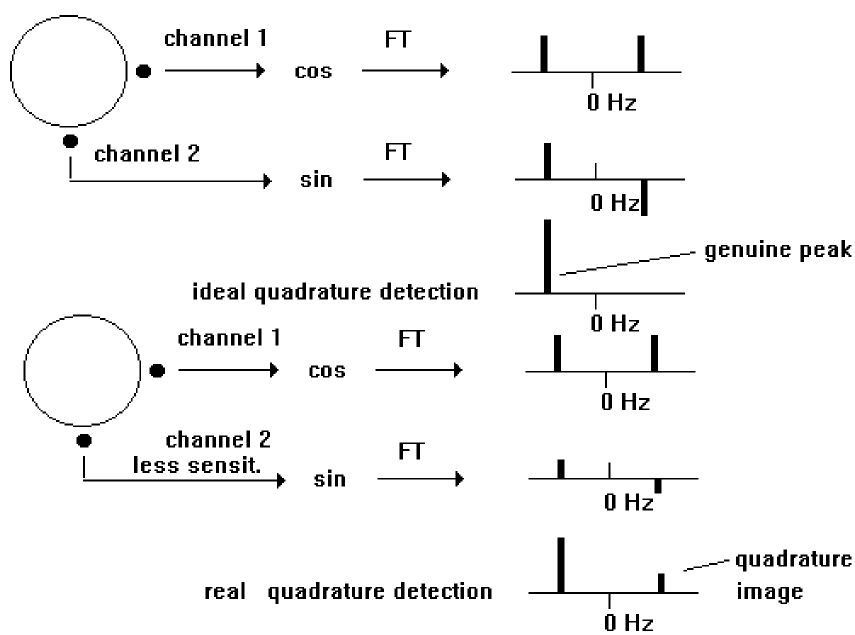
in quadrature detect. two identical channels are used (relative phase shift 90°)

quadrature glitch : artefacts by the diff. between the dc (direct current) baseline offset in chan.1 and chan. 2

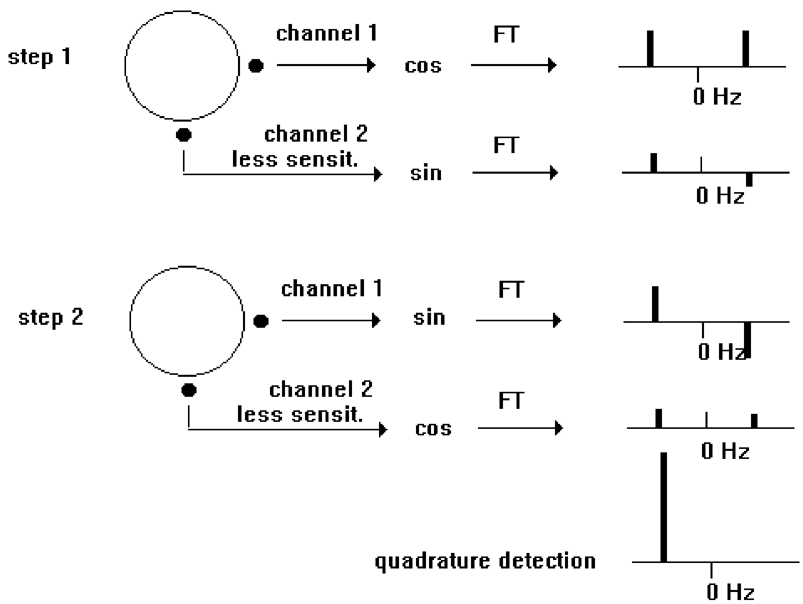
quadrature image: diff sensitivity of the two channels



the quadrature image

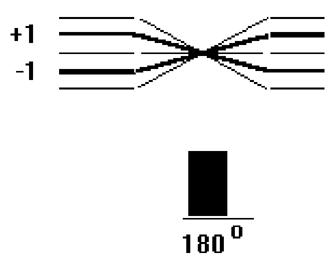


The answer is a 2 step CYCLOPS



memo : a 4 step CYCLOPS (0, 90, 180, 270) also removes signal from DC.

EXORCYCLE: compensate imperfect 180°



Pulse phase (ϕ)	Δp (-1- [p])	$-\Delta p\ \phi$	equi. cycle ($0^o \leq ... \leq 360^o$)	rec. phase set to	spectrum
single qunat. coh. p = +1					
0	-2	0	0	0	+a
90	-2	180	180	180	+a
180	-2	360	0	0	+a
270	-2	540	180	180	+a
single qunat. coh. p = -1					
0	+2	0	0	0	+a
90	+2	-180	180	180	+a
180	+2	-360	0	0	+a
270	+2	-540	180	180	+a
zero qunat. coh. $\Delta p = 0$					
0	0	0	0	0	+a
90	0	0	0	180	-a
180	0	0	0	0	+a
270	0	0	0	180	-a

We have retained **-6, -2, +2, +6** etc.

$\Delta p = 0$ (unrefocused magnetisation)
$\Delta p = \pm 1$ (coherence transfer proc.) are eliminated.

Axial peak suppression:

during free precession (t_1, Δ, $\tau_{mix.}$) magnetisation relax toward equ.
conclusion : before ACQ, we have a peak at $F_1 = 0$

answer : phase cycling the pulse before : t_1, Δ, $\tau_{mix.}$ etc.
common procedure: phase cycling the first pulse (2 step.)

memo : 2D-NOESY (32 step phase cycle) 4*2*4 {NOESY * axial peak[$\tau_{mix.}$]*CYCLOPS}
2D-COSY (8 step phase cycle) 2*4 { axial peak[t_1] *CYCLOPS}
2D-DQFCOSY (32 step phase cycle) 4*2*4 {DQ * axial peak[$\tau_{mix.}$]*CYCLOPS}

limitations : difference method

sensitive toward changes
- pulse amplitude
- phase changes of a pulse
- field-frequency
- temperature
- lock frequency

lengthy : full relaxation should be obtained (rd.)

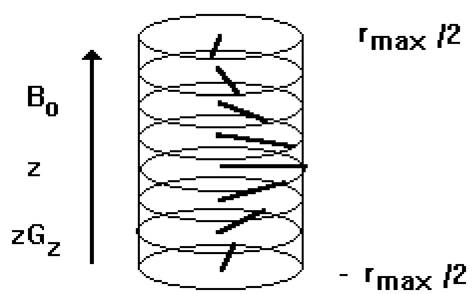
COHERENCE SELECTION via PULSED FIELD GRADIENT:

B_o is made inhomogeneous, which dephase or refocuse previously dephsed coherence. (A dephasing and refocusing pulse pair is a gradient echo.)

principle: the coherence dephasing (ϕ) is proportional to - γ (gyromagnetic ratios)
- p (coherence order)

prev. tech. problem: - the field gradient influenced the "lock" .
- the field gradient caused large eddy currents

answer: active shielding



The effect of the gradient pulse : spatially (z) dependent phase is made from a uniform phase

The gradient produces an "extra" magnetic field : $B_g(z)$

$B_g(z) = z\,G_z$ where G_z := grad. strength (T/m or G/cm)
z := z "type" distance

$B_{eff} = B_o + B_g(z)$

the Larmor frequ. vary as function of z

$\omega(z) = -\gamma\,[B_o + B_g(z)] = -\gamma\,[B_o + z\,G_z] = \omega_o - \gamma z G_z$

comment : in the rotating frame the frequency is $\gamma z G_z$
after time *t* the spatial dephasing [$\phi(z)$] is $\gamma z G_z t$

Lets consider an in-phase single quant. coh. (I_x) -> M_x (t) ≈ I_x(t)

Then the variation of the bulk magnetisation M_x (t)

- with no gradient:

$$I_x \quad \text{--}I_z(t)\text{-->} \quad \cos(t)\, I_x + \sin(t)\, I_y$$

the net x magnetisation across the whole sample:

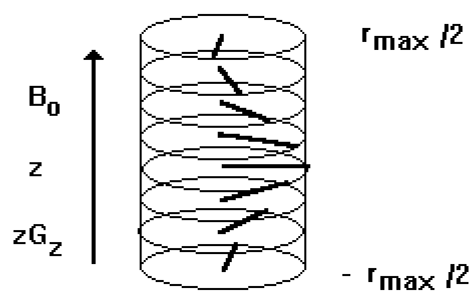
$$M_x(t) = \frac{1}{r_{\max}} \int_{-r_{\max}/2}^{r_{\max}/2} \cos(t)\,dz = \cos(t)$$

- with gradient:

$$I_x \quad \text{--}\{-\gamma z G_z t I_z\}\text{-->} \quad \cos(\gamma z G_z t)\, I_x + \sin(\gamma z G_z t)\, I_y$$

net x magnetisation across the whole sample:

$$M_x(t) = \frac{1}{r_{\max}} \int_{-r_{\max}/2}^{r_{\max}/2} \cos(\gamma z G_z t)\,dz = \frac{2\sin(\gamma G_z t \frac{r_{\max}}{2})}{\gamma G_z t r_{\max}} = \sin c(\gamma G_z t \frac{r_{\max}}{2})$$



Conclusion : - M_x decay in an oscillating mode
- stronger gradient induces a faster decay
- decay is faster for a nuclei with higher gyromagnetic ratio

approximation: if t is long enough then the hyperbolic approximation holds:

$$M_x(t) = \frac{1}{\gamma G_z t \frac{r_{\max}}{2}} = \frac{2}{\gamma G_z t r_{\max}}$$

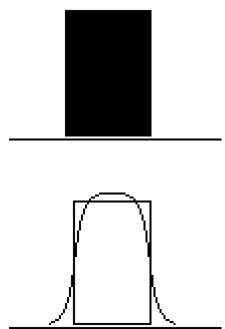
e.g. If a suppression of a ^1H is of interest ($\gamma = 2.6752\ E+8\ T^{-1}s^{-1}$)
in normal protein NMR sample r_{max} ≈ 3.25cm [0.0325m]
using a gradient G_z (30G/cm [0.3T/m])

if suppression is 0.1% of the orig. value -> 1E-3 = 2/[(3.25E-2*3E-1*2.6752E+8)*t]
t= 0.77 ms

As mentioned previously the coh. dephasing (ϕ) is proportional to
- γ (gyromagnetic ratios)
- p (coh. order)

ϕ (r,t) = s B_g(r)t $\Sigma\, p_i\gamma_i$ — $p_i\gamma_i$ gyromagnetic ratios and coh. level of nuclear species i
the gradient produces magnetic field : B_g(r)
s is the shape factor of the gradient pulse.

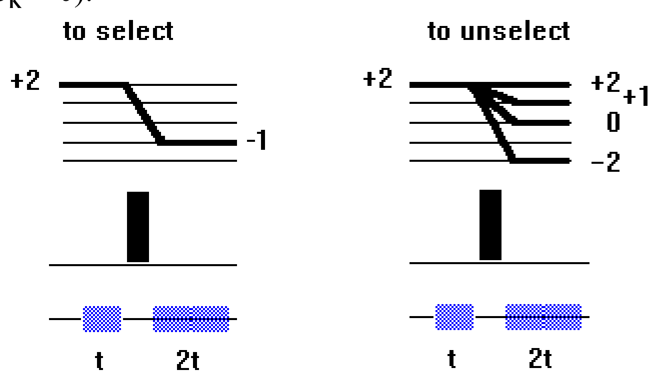
memo : grad. pulse is not rectangular pulse (at t=0 the slop is ∞ -> large eddy currents physical damage of the coil)



s = 1/t ∫ A(t) dt where abs[A(t)] ≤ 1

who to select the coherence transfer path?

A gradient echo is generated for the desired coherence transfer pathway.
The overall phase change for the selected coh. tran. pathway should be zero:
($\phi_i + \phi_k = 0$).

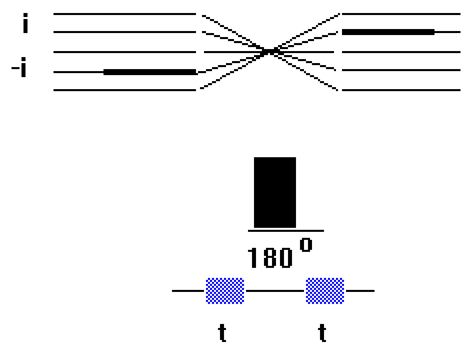


$\phi_i = s_1\, p_i\, B_{g1} t_1$
$\phi_k = s_2\, p_k\, B_{g2} t_2$

if p_i = +2 and p_k= -1, [s_1=s_2 and B_{g1}=B_{g2}]
then from (+2)*t_1+(-1)*t_2=0 -> $t_2 = 2t_1$

Artefact suppression

e.g. $-I_y$ ---(π I_x)--> $+I_y$ (spin echo)



The first gradient dephases and the second rephases (same sign, same strength)
effect of the +z gradient (τ) 180^o +z gradient (τ) :

- pulse imperfection eliminated
- transverse magnetisation of a diff. spin is removed

a limitation of pulsed field gradient:

if p_i --> p_j is selected by gradient then the $-p_i$ --> p_j can not be selected.
Since both pathways are required (frequency discrimination) the two pathways should be recorded sequentially.