Dynamic Nuclear Polarisation
(Continuous Wave)

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Menu

Starter

DNP in a nutshell

Main Course

Trio of DNP mechanisms:
Solid effect, Overhauser Effect, and Cross Effect

Dessert

A selection of experimental details

The saying goes, there are three problems with NMR…

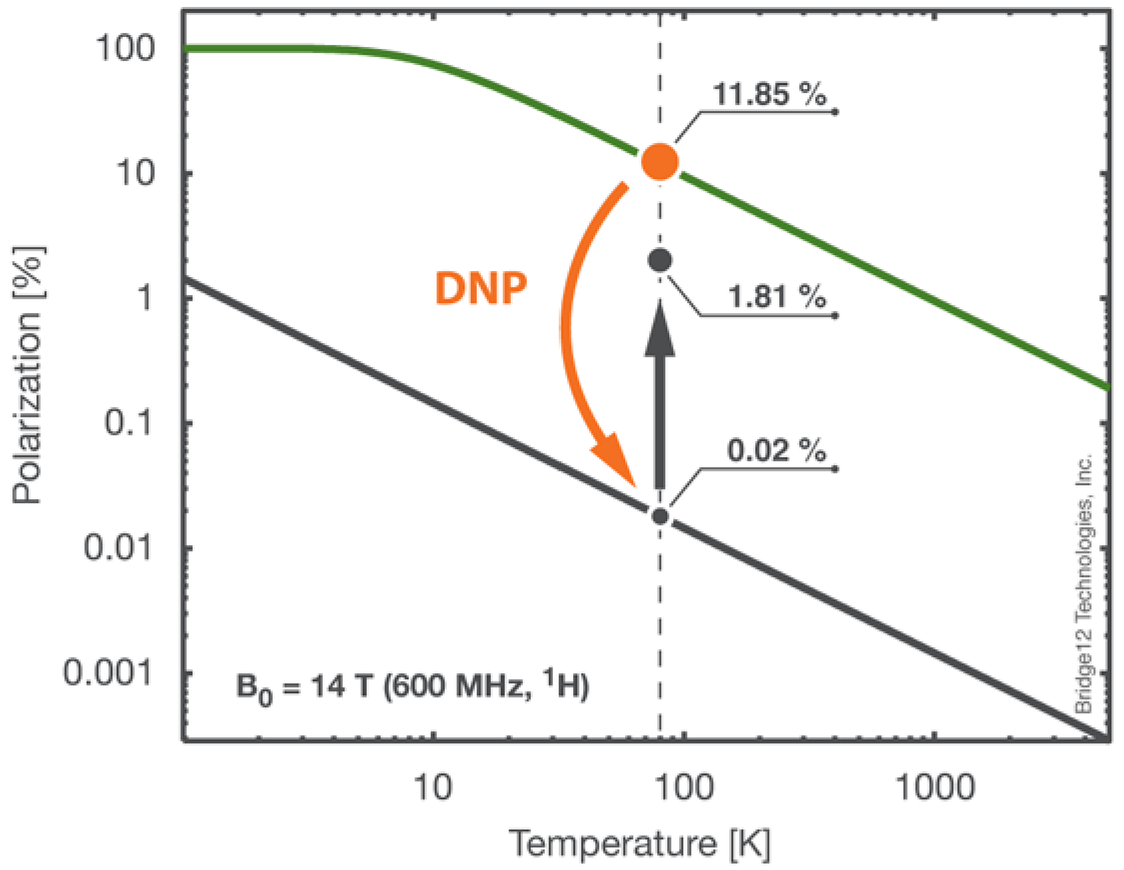
…sensitivity, sensitivity, and sensitivity!

-Various sources

NMR Signal ∝ Spin Polarisation

$$P = \tanh\left(\frac{\hbar\gamma B_0}{2k_\mathrm{B}T}\right) \approx \frac{\hbar\gamma B_0}{2k_\mathrm{B}T}$$

- ^{1}H at 600 MHz, 100 K:
  $$P = 0.02\%$$
- $\gamma_e = 658\,\gamma_H, \quad P = 12\%$
- DNP: transfer polarisation from electrons to nuclei!



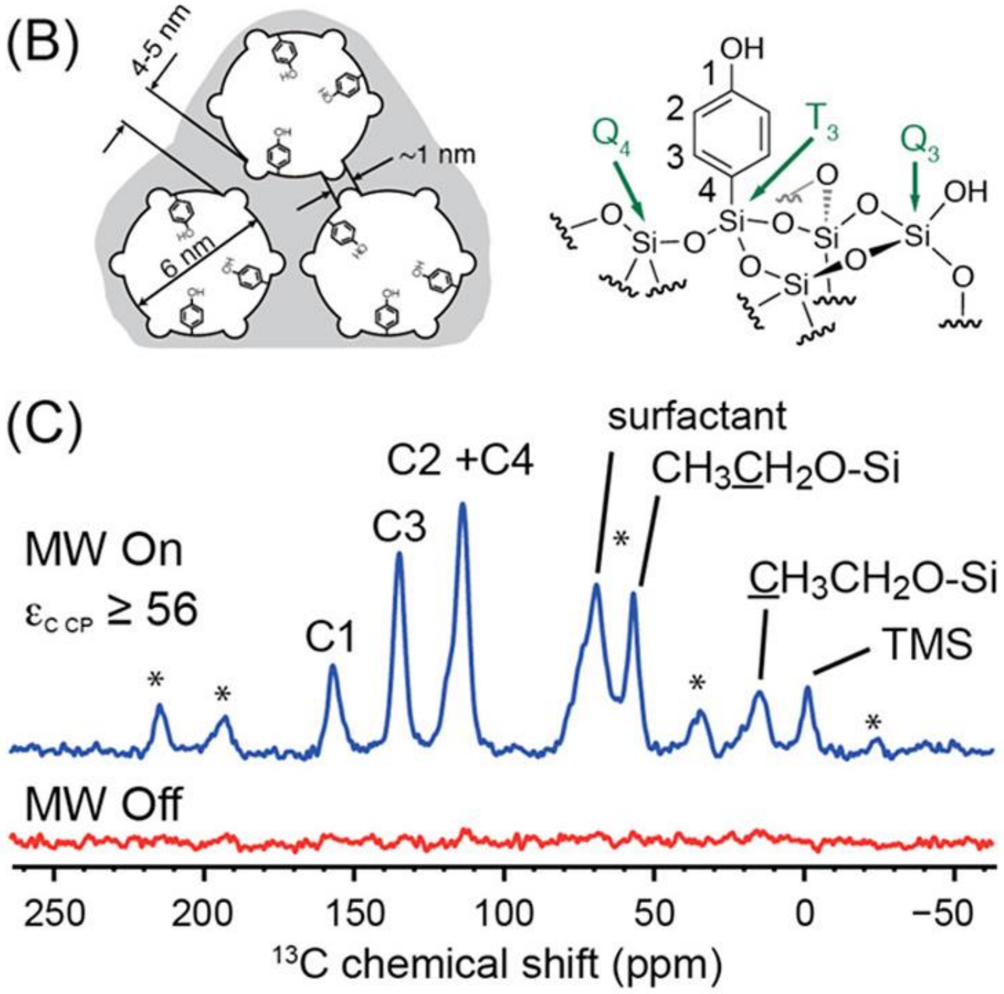
An Example

DNP enable experiments that would be impractically long otherwise

E.g. natural abundance ^{13}C of low concentration organic species on silica surfaces

Enhancement, $\varepsilon = I_{\mathrm{ON}}/I_{\mathrm{OFF}}$

(>3000× time saving)



34 min

Rossini et al., *Acc. Chem. Res.*, 2013.   Lesage et al., *JACS*, 2010

DNP 101

Add source of unpaired electrons → Cool to ~100 K → Apply high power microwaves

Typically organic radicals

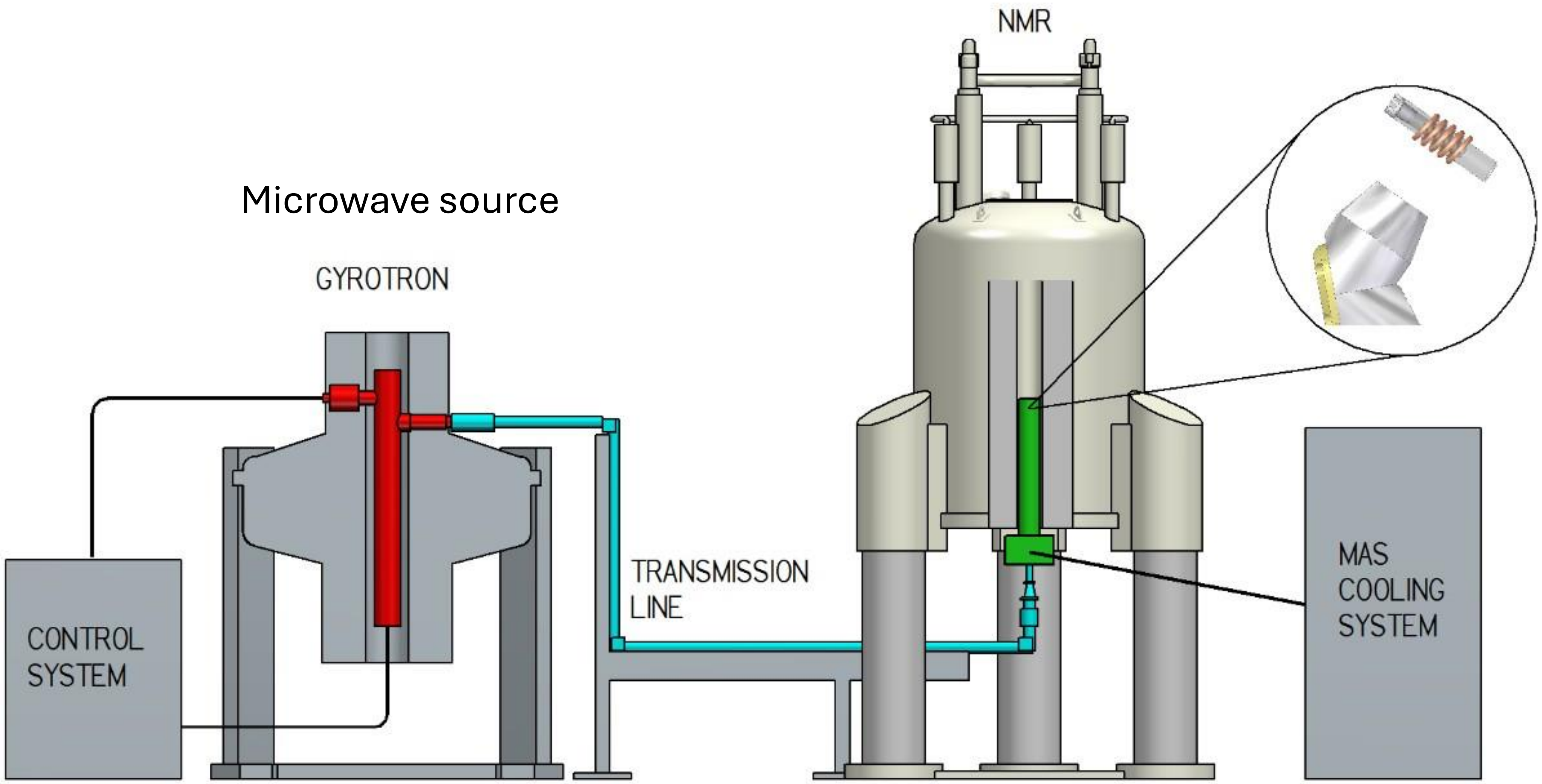
Sometimes paramagnetic metal ions

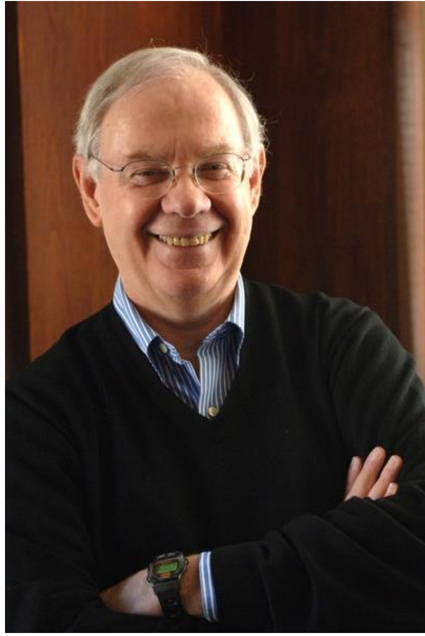
Slow electron relaxation

At or near the EPR frequency

DNP instrumentation

Microwave source





Bob Griffin
MIT

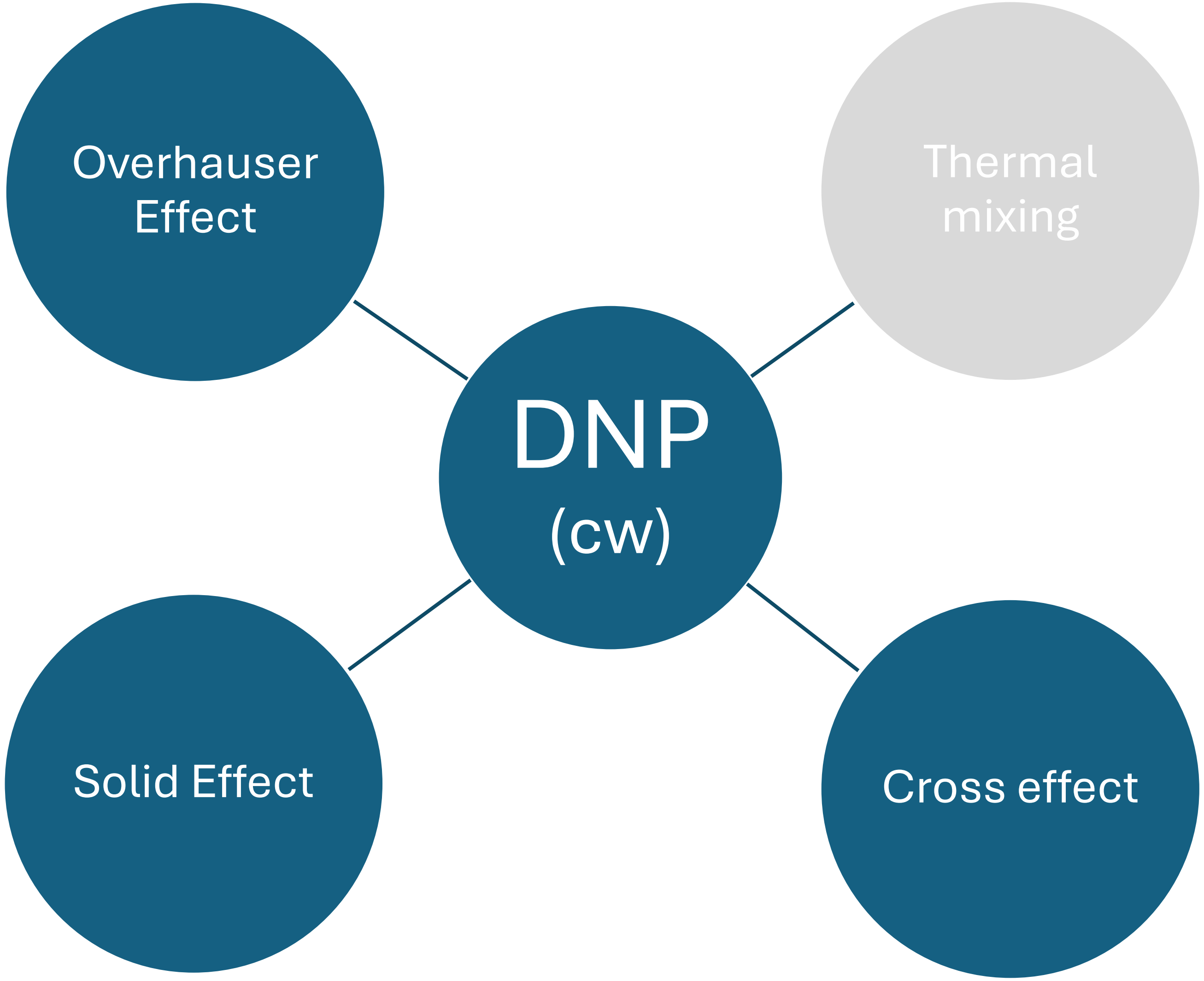
MAS at ~100 K

DNP instrumentation

University of Nottingham DNP MAS NMR Facility, UK

How to transfer polarisation?

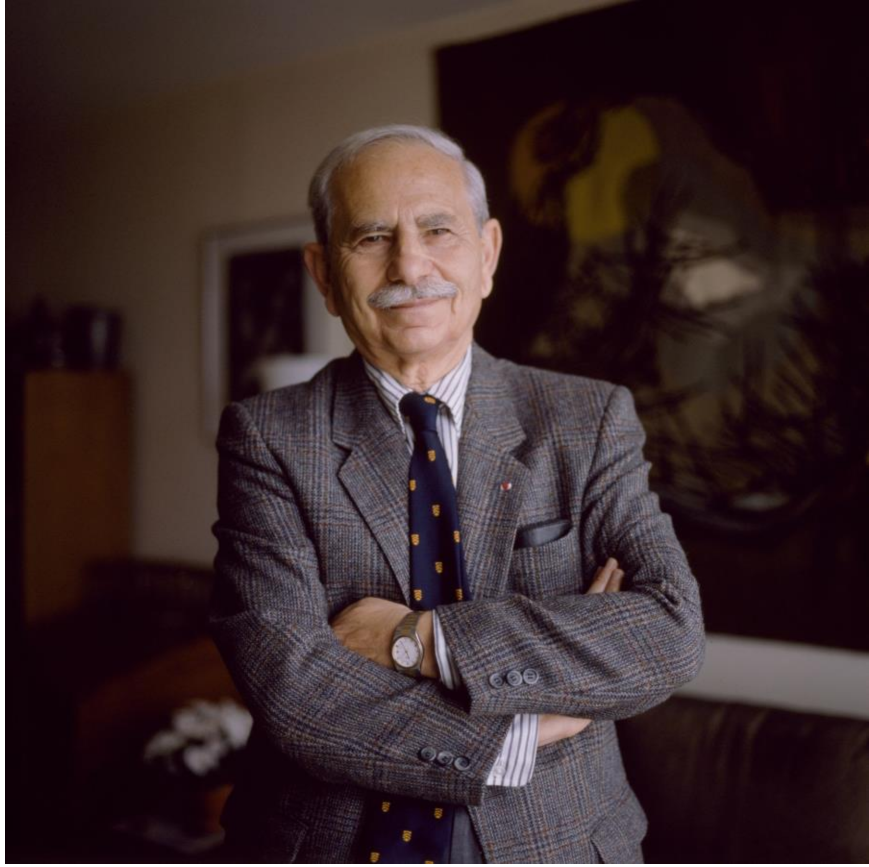
- First example of DNP
- Now mainly liquids



- High conc. of radicals
- Low T (<10 K)

- Most common for MAS DNP!

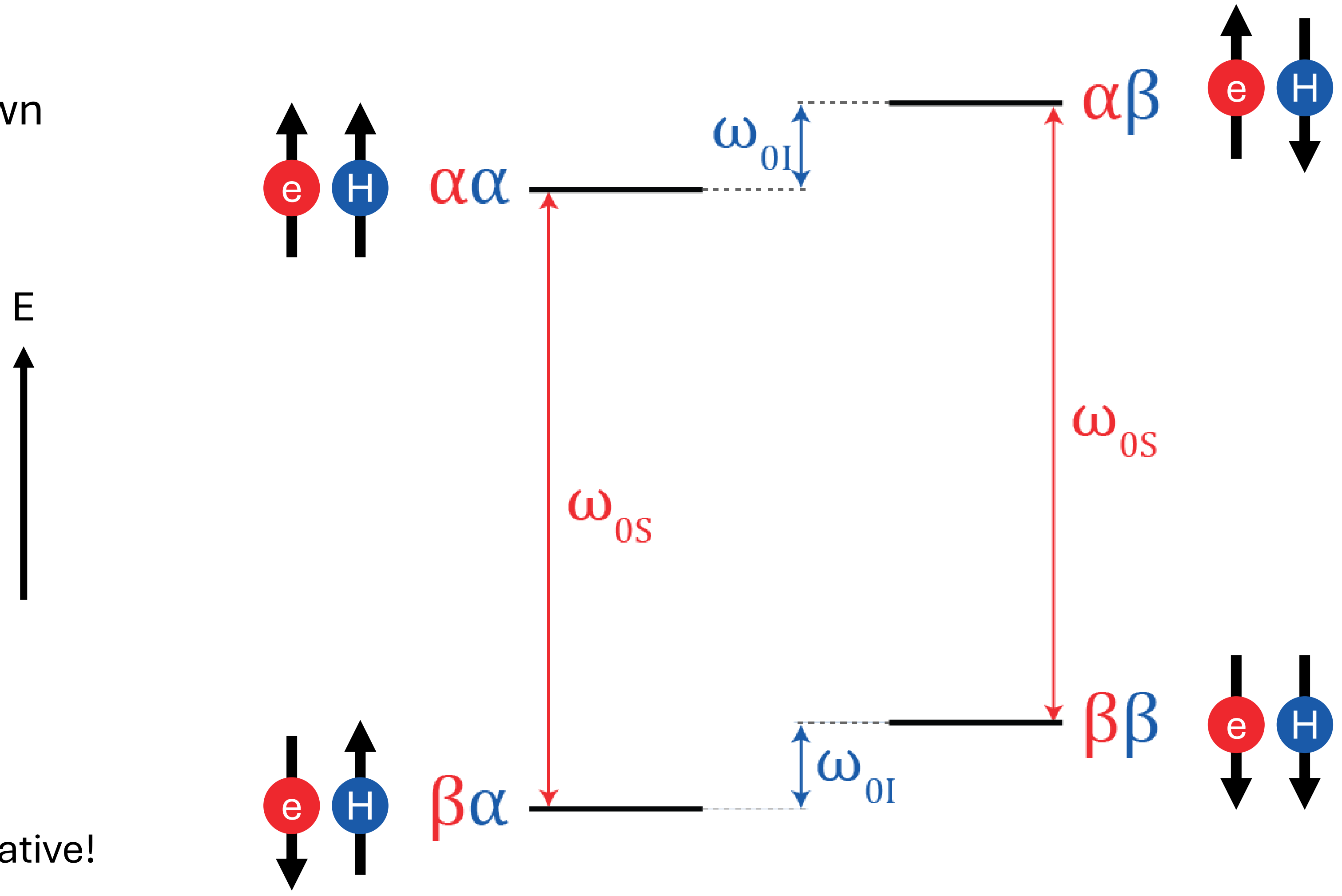
Solid Effect



Anatole Abragam

The electron-nuclear two-level system

α = spin up
β = spin down

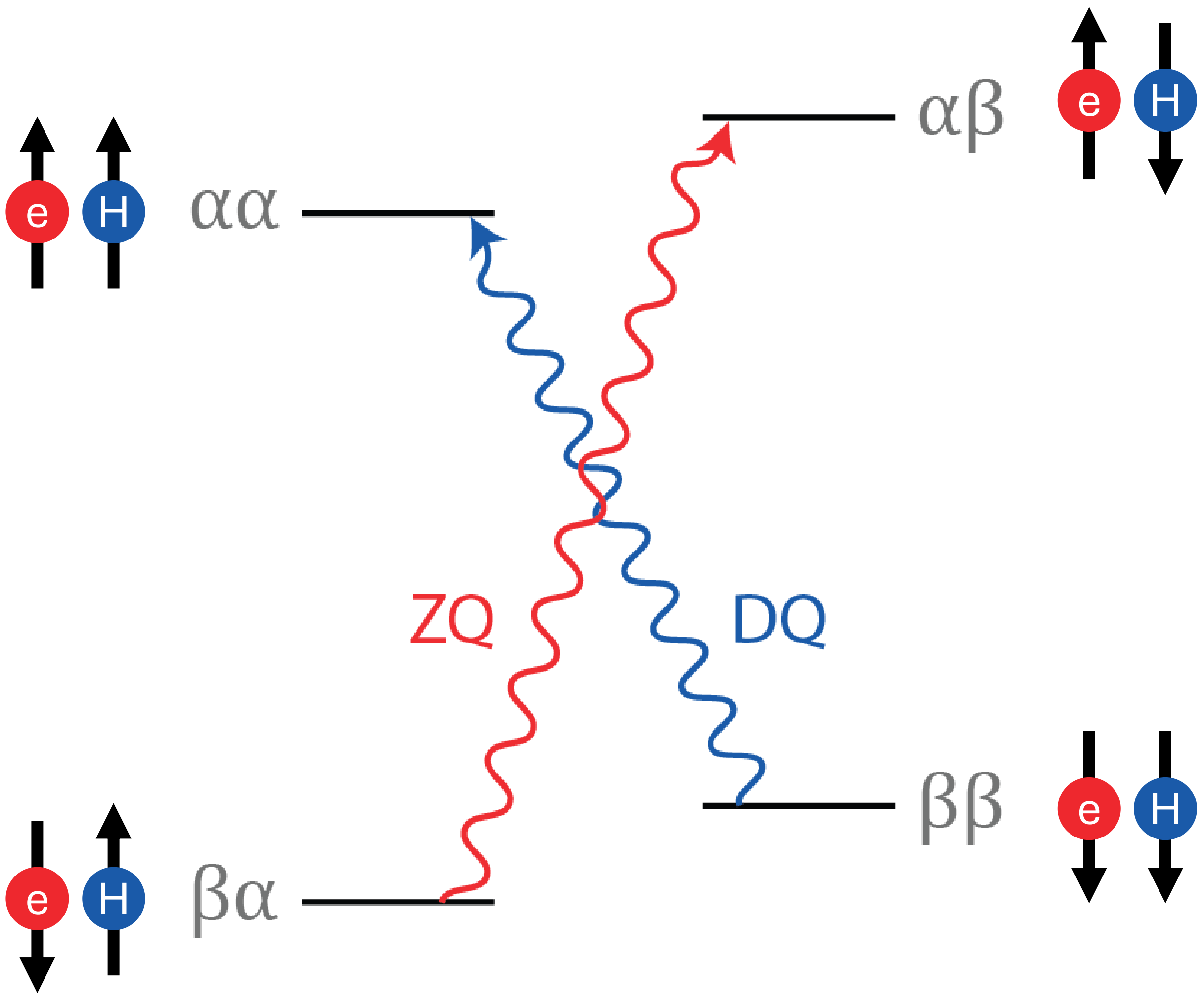


$$\Psi = |m_S m_I\rangle$$

electron nucleus

Note: γ_e is negative!

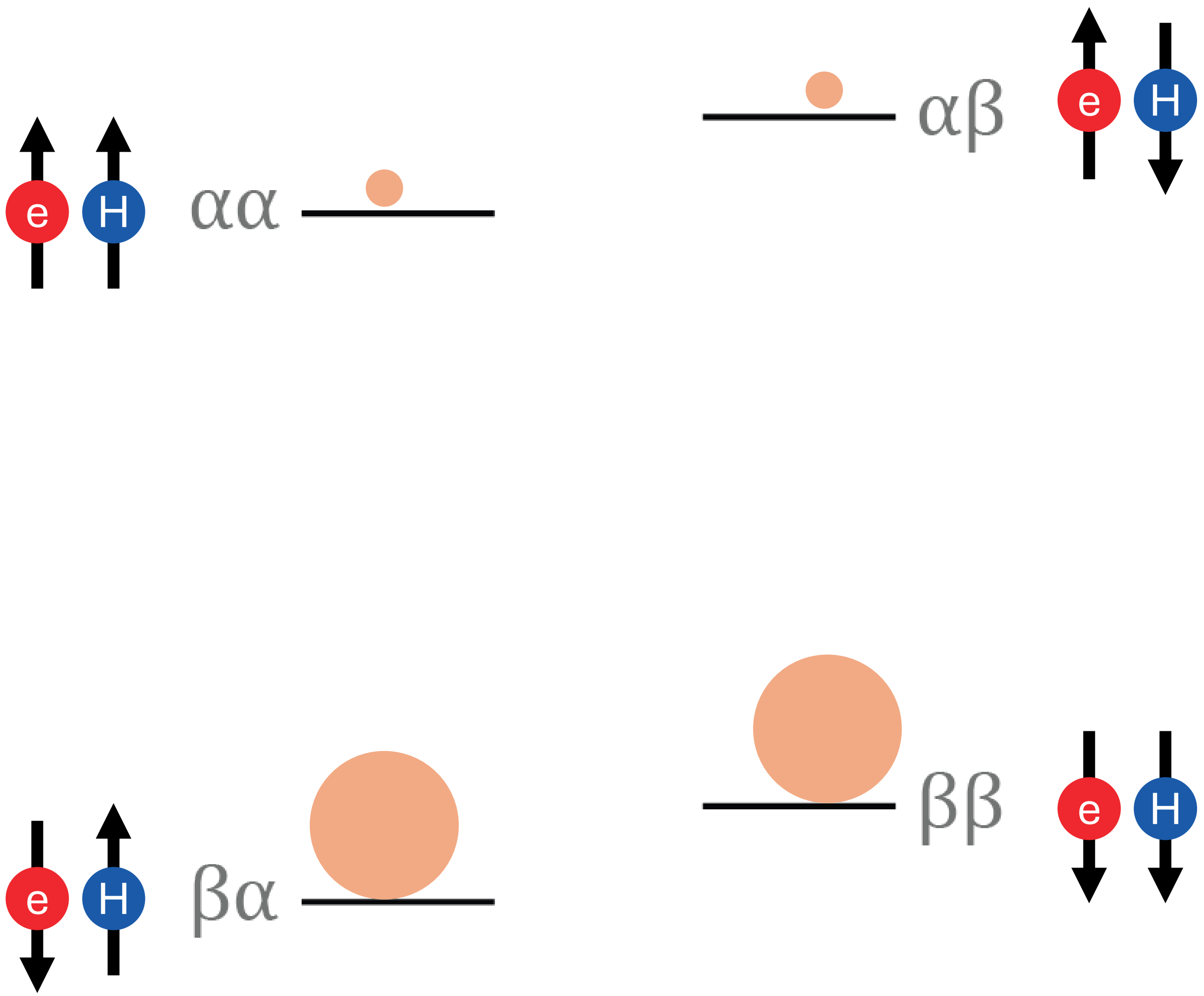
Solid Effect: ZQ and DQ transitions



- ZQ = zero quantum
- DQ = double quantum

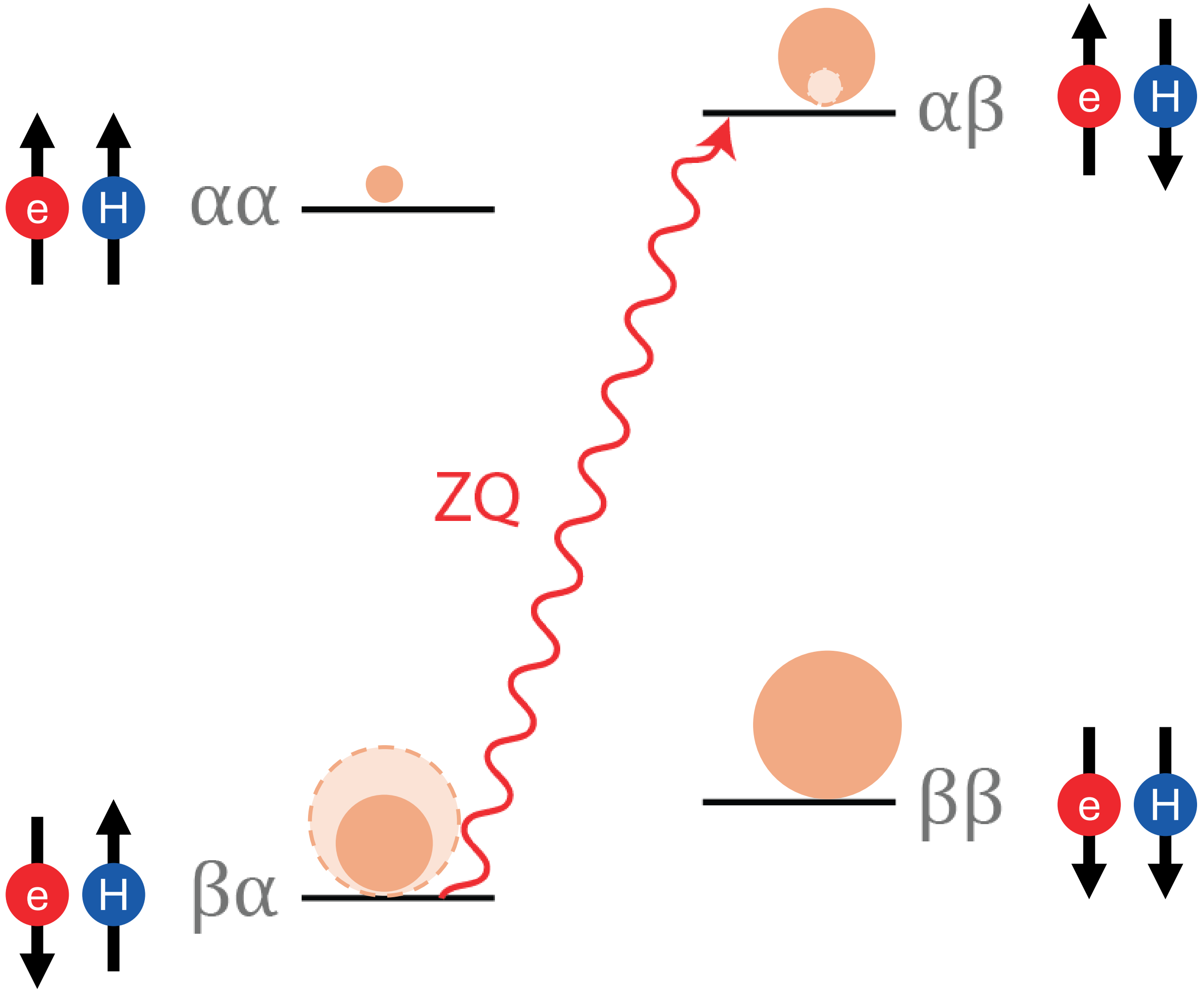
- Simultaneously flip electron and nuclear spin

Solid Effect: Populations



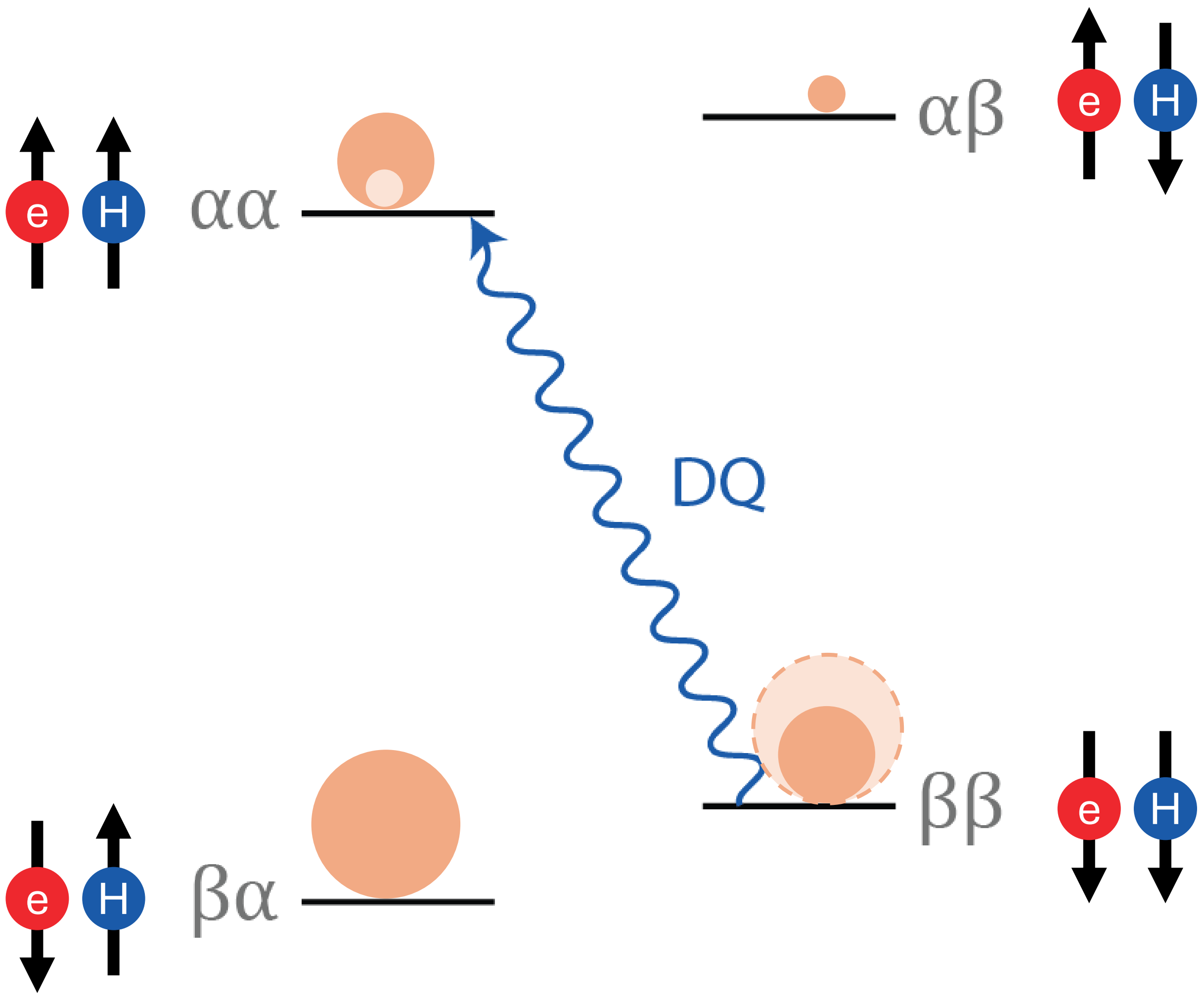
- Thermal equilibrium
- Electron spin polarisation: big (population difference)
- Nuclear spin polarisation: small (similar population)

Solid Effect: Saturating ZQ Transition



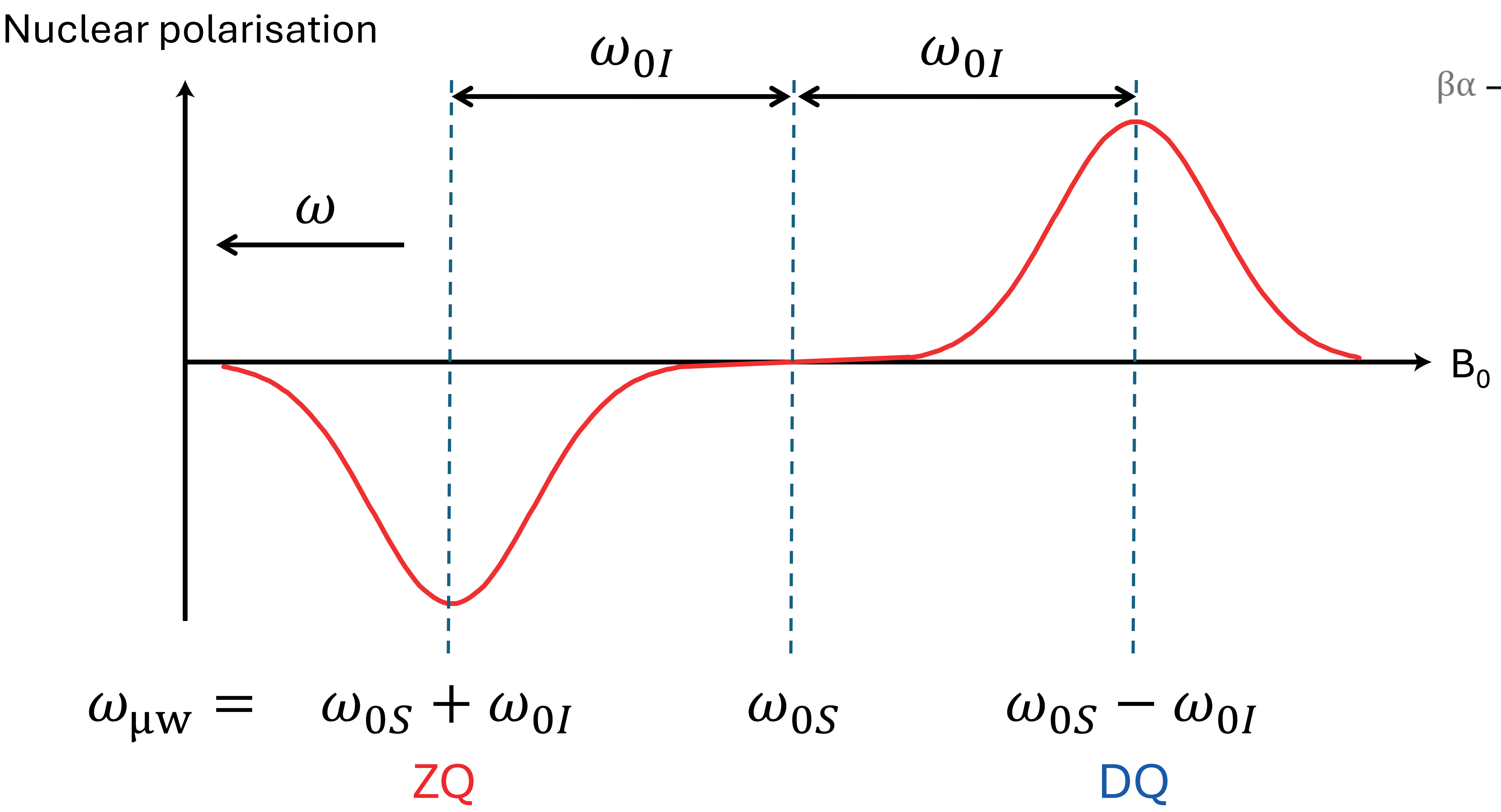
- CW microwaves act to equilibrate the populations
- Electron spin polarisation: reduced
- Nuclear spin polarisation: large negative enhancement

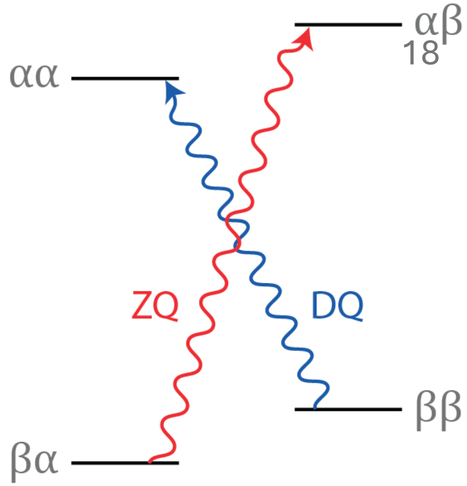
Solid Effect: Saturating DQ Transition



- CW microwaves act to equilibrate the populations
- Electron spin polarisation: reduced
- Nuclear spin polarisation: large positive enhancement

Solid effect: Field Profile





But wait…

multiple quantum transitions are forbidden!

Let’s look at some maths

Pseudosecular coupling

- $\hat{H}_I = -\omega_{0I}\hat{I}_z + \hat{\boldsymbol{S}} \cdot \mathbb{A} \cdot \hat{\boldsymbol{I}}$
- $\hat{H}_I = -\omega_{0I}\hat{I}_z + A_{zz}\hat{S}_z\hat{I}_z + A_{zx}\hat{S}_z\hat{I}_x$
- $\hat{H}_I = -\omega_{0I}\hat{I}_z + A\hat{S}_z\hat{I}_z + B\hat{S}_z\hat{I}_x$

- A = secular coupling
- $B = \sqrt{A_{zx}^2 + A_{zy}^2}$ (in general)

  "Pseudosecular coupling"

$$\hat{\boldsymbol{S}} = \begin{pmatrix} 0 \\ 0 \\ \hat{S}_z \end{pmatrix}$$

Electron.
Zeeman dominates, aligned with B_0 (z) (secular approx. for *S*)

$$\hat{\boldsymbol{I}} = \begin{pmatrix} \hat{I}_x \\ \hat{I}_y \\ \hat{I}_z \end{pmatrix}$$

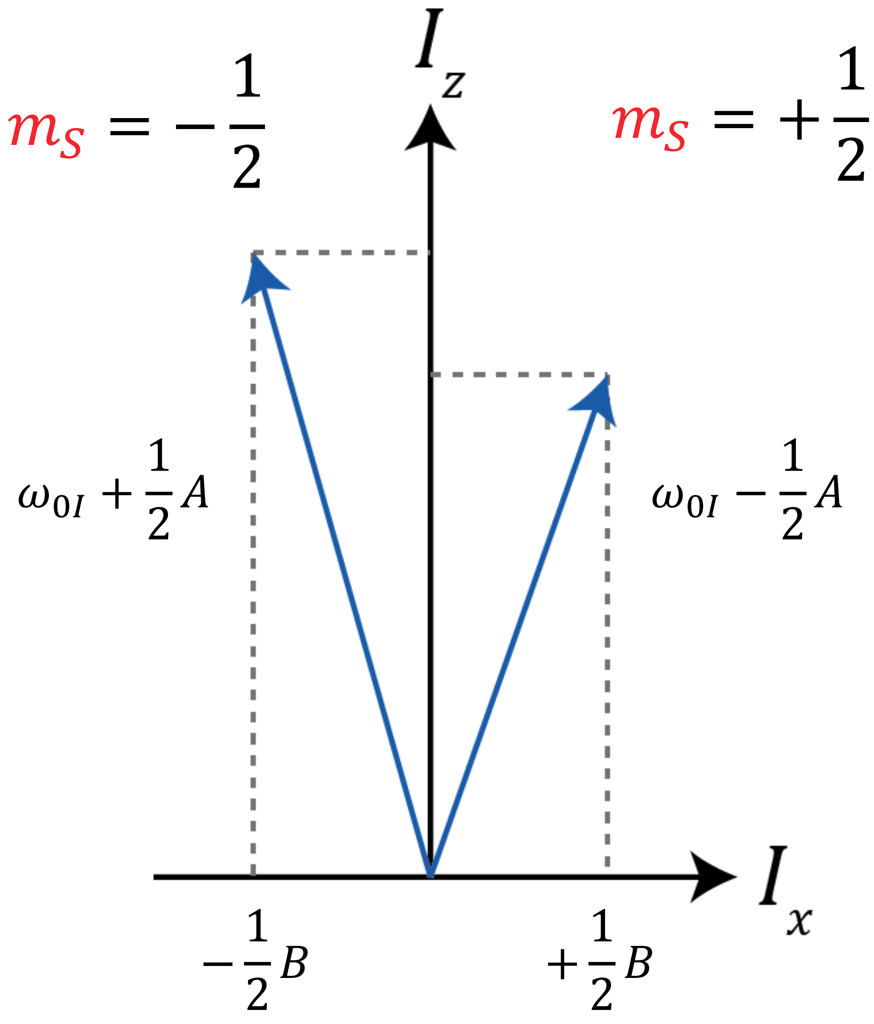
Nucleus.
Hyperfine coupling perturbs. Can't assume aligned with z

$$\mathbb{A} = \begin{pmatrix} A_{xx} & 0 & A_{xz} \\ 0 & A_{yy} & 0 \\ A_{zx} & 0 & A_{zz} \end{pmatrix}$$

Hyperfine coupling.
Assume electron and nucleus in xz plane

Thankamony et al., Prog. Nucl. Magn. Reson. Spectrosc., 2017.
epr.ethz.ch/education/basic-concepts-of-epr/

Tilting of axis of quantisation



$$\hat{H}_I = (-\omega_{0I} + A\hat{S}_z)\hat{I}_z + B\hat{S}_z\hat{I}_x$$

$$\hat{S}_z\psi = m_S\psi = \pm\frac{1}{2}\psi$$

- Quantisation axis is tilted away from z (equivalent to mixing of α and β)
- Orientation depends on the electron spin state

Electron State	Nuclear Eigenstates
α	$\alpha + \delta\beta$ $\beta - \delta\alpha$
β	$\alpha - \delta\beta$ $\beta + \delta\alpha$

High field limit:

$$\delta = \frac{B}{4\omega_{0I}} < 1\%$$

State mixing enables transitions

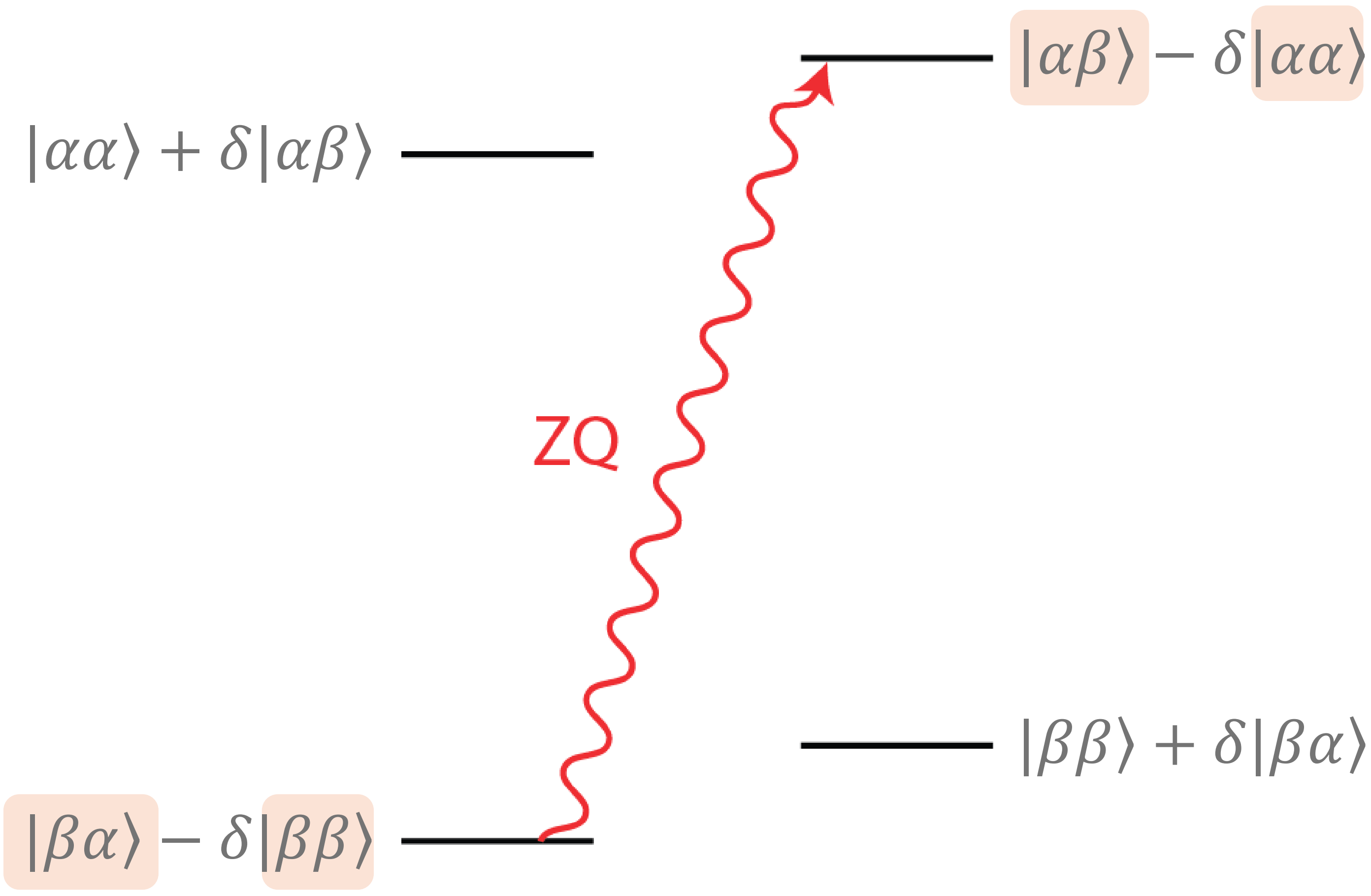
$$|\alpha\beta\rangle - \delta|\alpha\alpha\rangle$$

$$|\alpha\alpha\rangle + \delta|\alpha\beta\rangle$$

$$|\beta\beta\rangle + \delta|\beta\alpha\rangle$$

$$|\beta\alpha\rangle - \delta|\beta\beta\rangle$$

State mixing enables transitions



- Transitions are allowed between the mixed-in states
- Overall the transitions become weakly allowed, depending on the size of the pseudosecular coupling

$$\delta = \frac{B}{4\omega_{0I}}$$

- Pseudosecular coupling requires anisotropic e-n coupling. Not possible in (isotropic) liquids!

What limits the enhancement?

Enhancement is determined by how efficiently we can saturate the ZQ or DQ transition.

Strength of e-n pseudosecular hyperfine coupling vs. ω_0

Short e-n distance, lower B_0

EPR linewidth and relaxation.

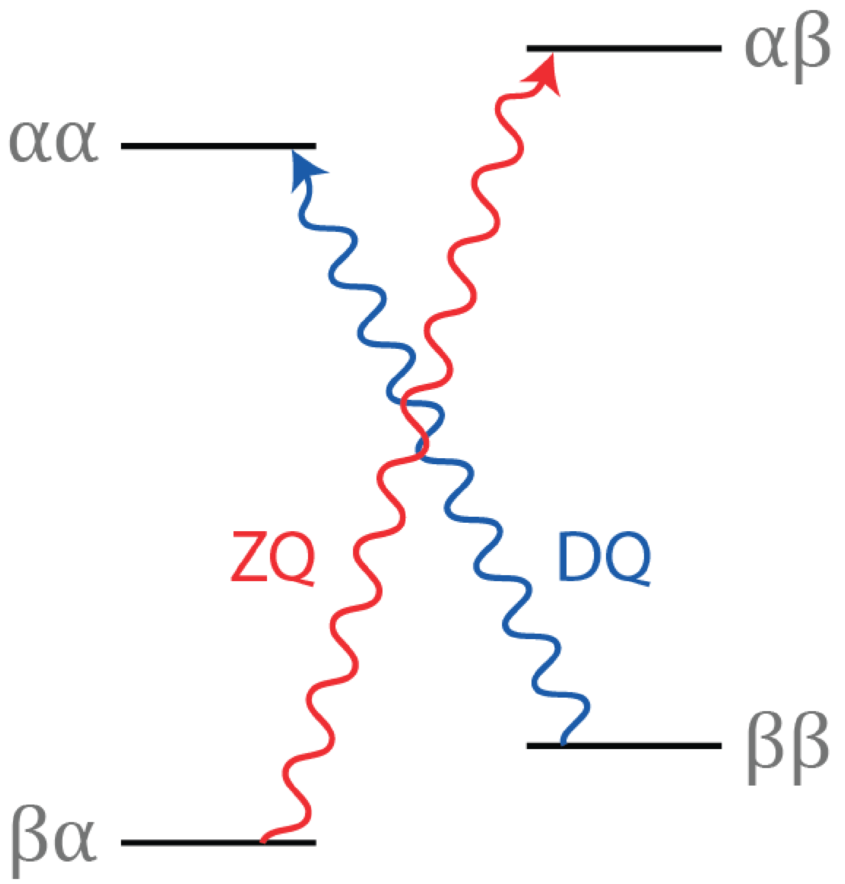
Narrow line and long T_{1e} easier to saturate

Microwave power. Transitions are only weakly allowed so typically need high microwave powers

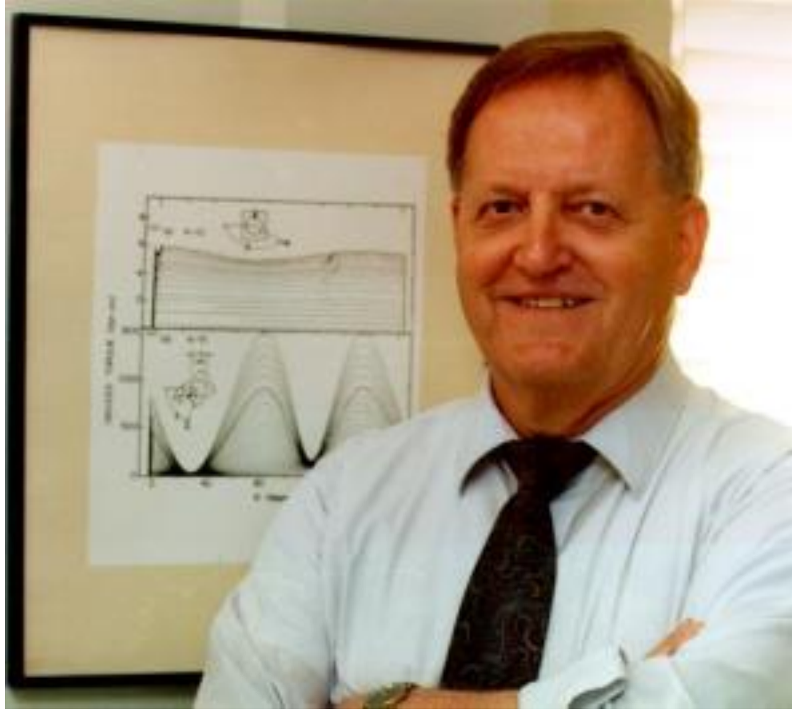
$$\varepsilon \propto \delta^2 \propto \frac{A_{zx}^2}{\omega_{0I}^2} \propto \frac{1}{B_0^2}$$

Summary: Solid Effect

- Microwaves drive ZQ or DQ transitions in e-n two spin system
- Simultaneously flip both spins. Transfer polarisation from electron to nucleus
- Requires anisotropic e-n coupling. Not possible in isotropic liquids



Questions?



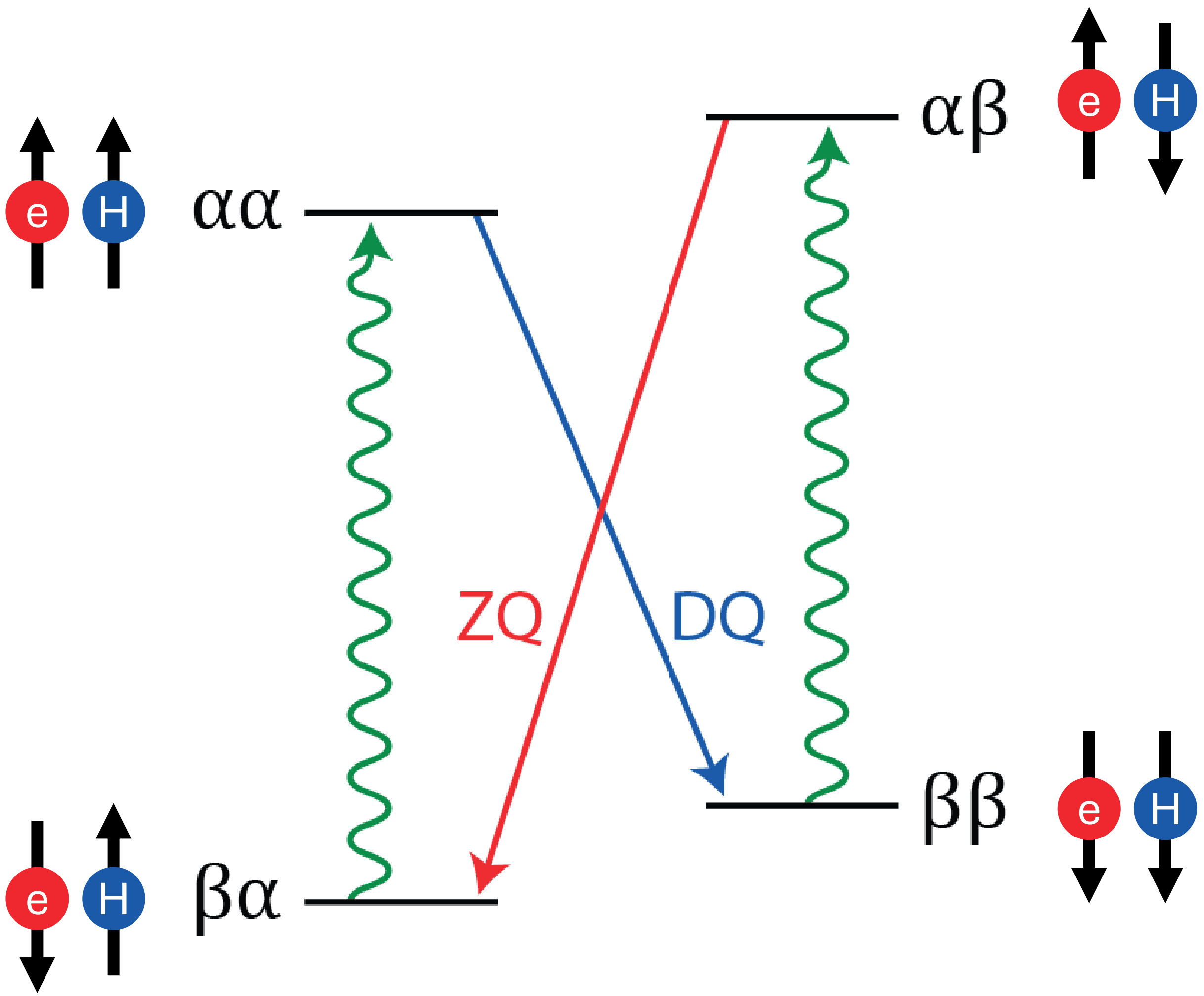
Overhauser Effect

“The discovery of dynamic nuclear polarisation took me two days”

-Albert Overhauser

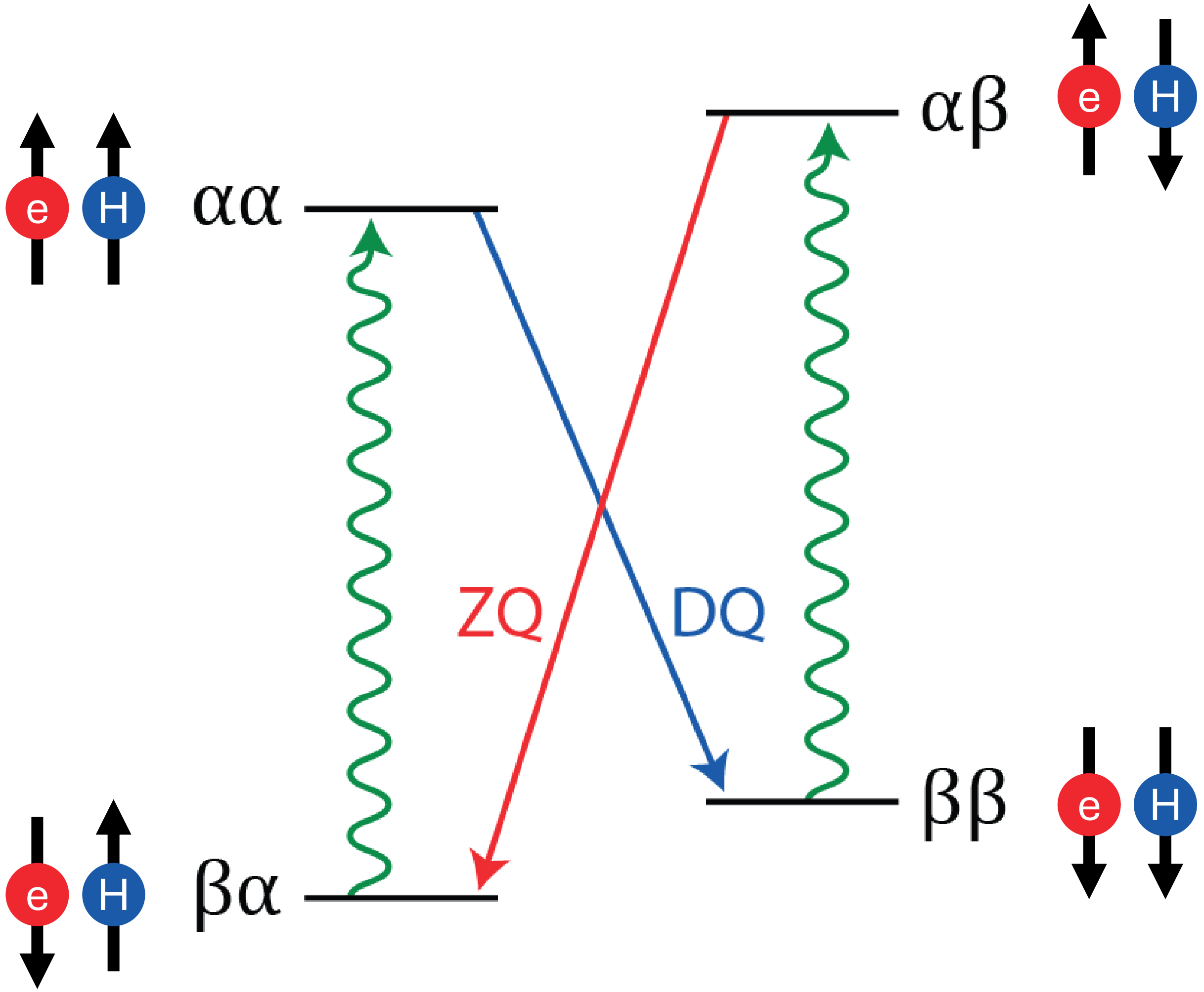
(Experimental proof by Carver and Slichter in 1953 took about 9 months)

Overhauser Effect



- Saturate allowed single quantum transitions with microwaves
- Cross-relaxation generates nuclear hyperpolarisation
- If ZQ and DQ rates are different

Overhauser Effect Enhancement Sign



- Sign of OE enhancement depends whether ZQ or DQ relaxation dominates

ZQ > DQ

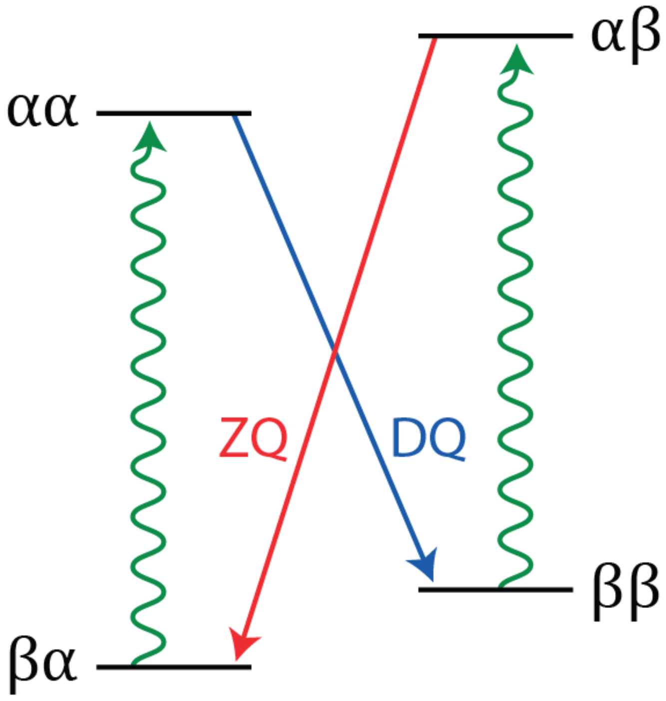
Positive ε

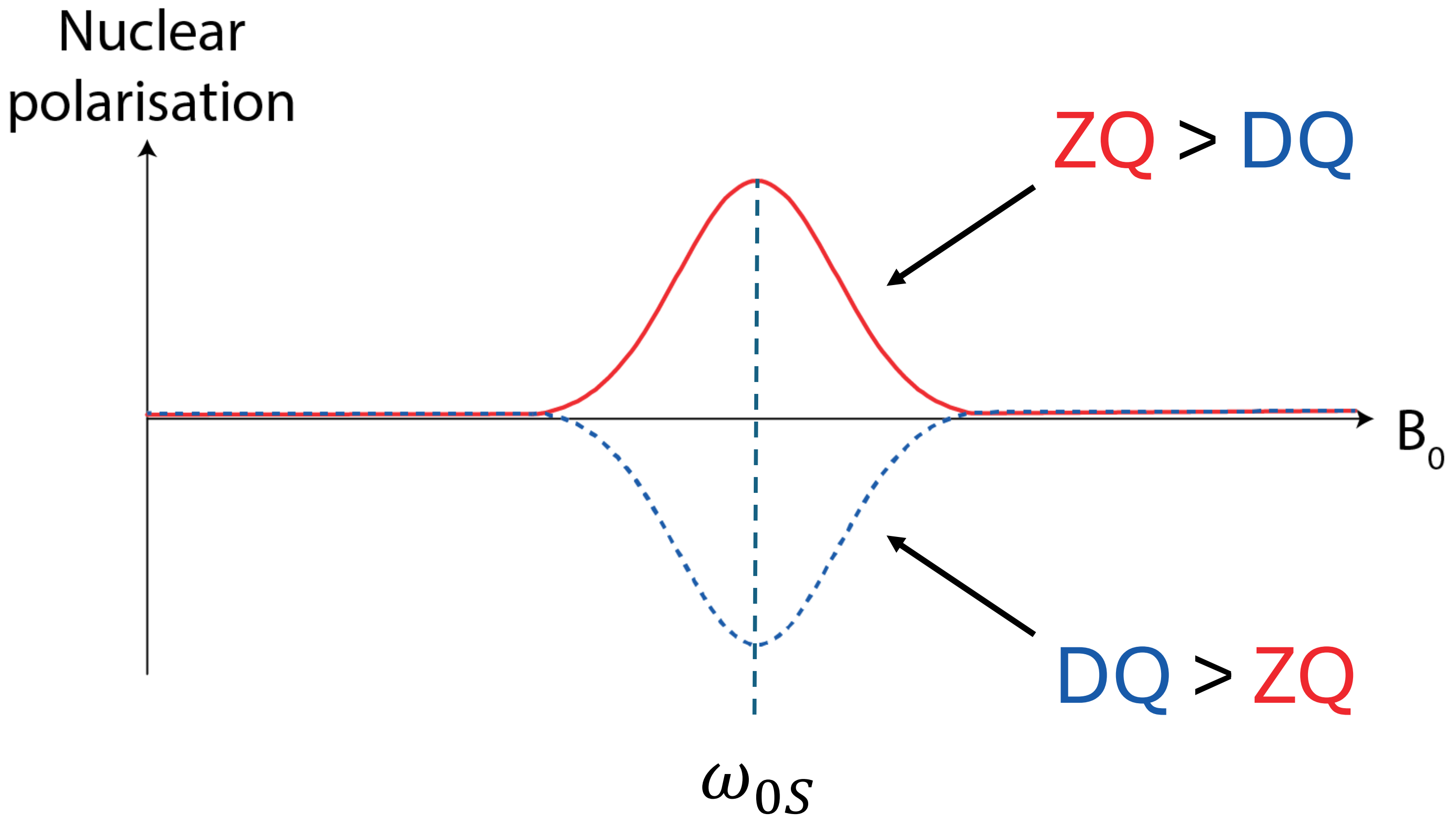
DQ > ZQ

Negative ε

- Unlike SE, we can't choose the sign!

Overhauser Effect Field Profile





What determines relaxation rates?

Solomon Theory

Ionel Solomon

- Cross relaxation is driven by fluctuations in the hyperfine coupling at around the EPR frequency
- Hyperfine coupling can have scalar (Fermi contact) and/or dipolar components: $\mathbb{A} = A^{\mathrm{FC}} + \mathbb{A}^{\mathrm{dip}}$

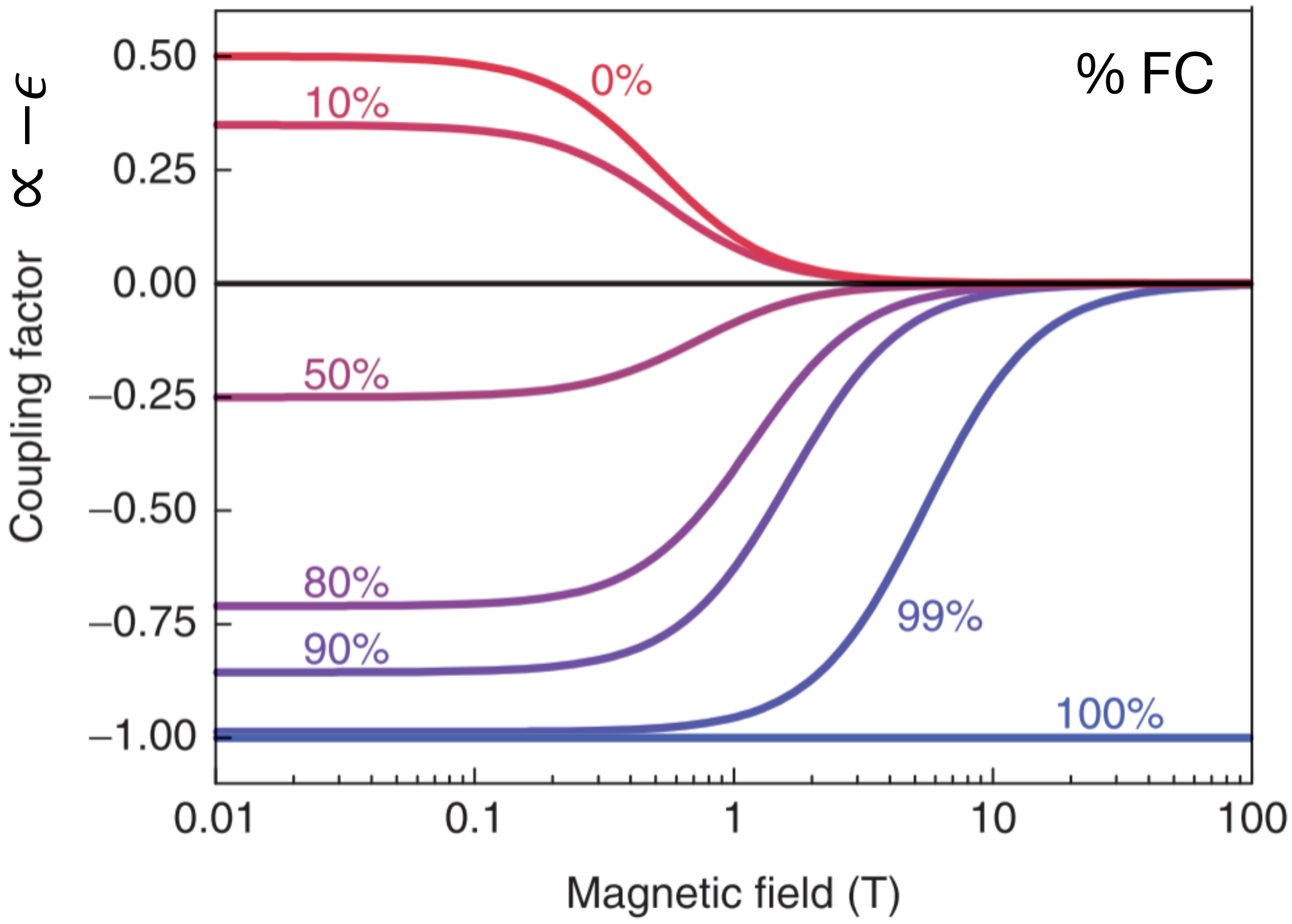
Fermi Contact

- Only ZQ relaxation possible
- Positive enhancement

Dipolar Coupling

- DQ > ZQ
- Negative enhancement
- Above ~1 T, SQ nuclear relaxation is too fast: no enhancement!

Overhauser Effect Field Dependence



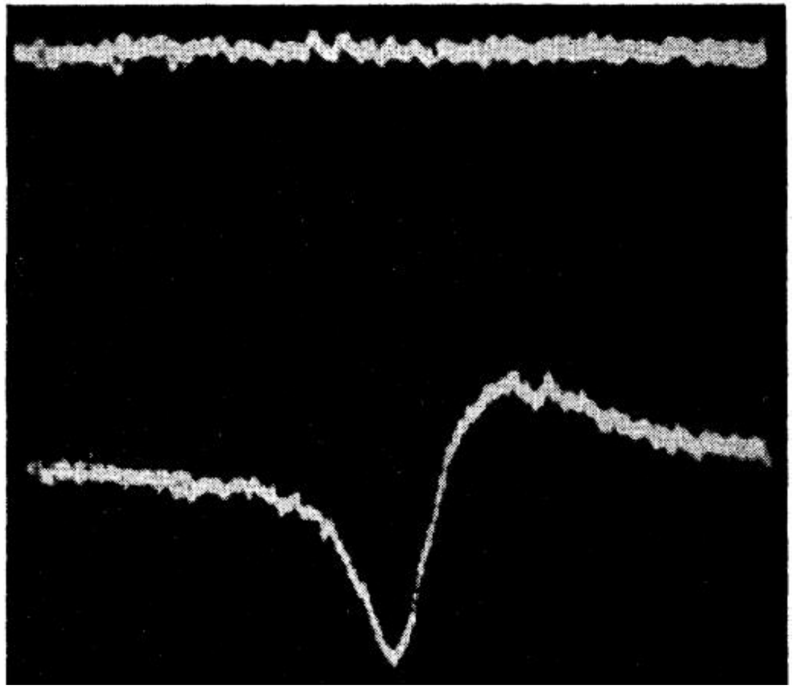
- Pure Fermi Contact: Positive enhancement
- Dipolar coupling: Negative enhancement, only at low field
- Any dipolar contribution eventually kills OE

Bennati and Orlando, eMagRes, 2019

Overhauser Effect in Metals

- In metals, fluctuations are caused by fast moving conduction electrons
- Electrons at the Fermi level have a velocity of ~1×10^6 m/s
- Fermi contact dominates

^{7}Li NMR of Li Metal



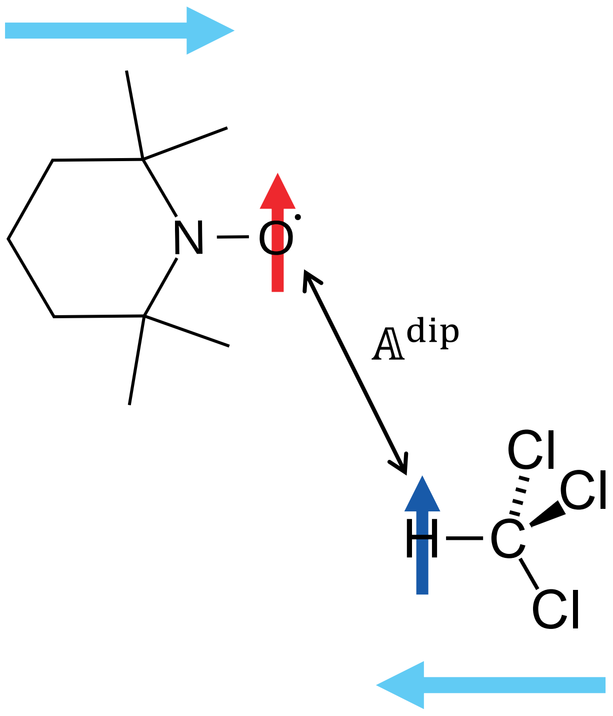
μw off

μw on

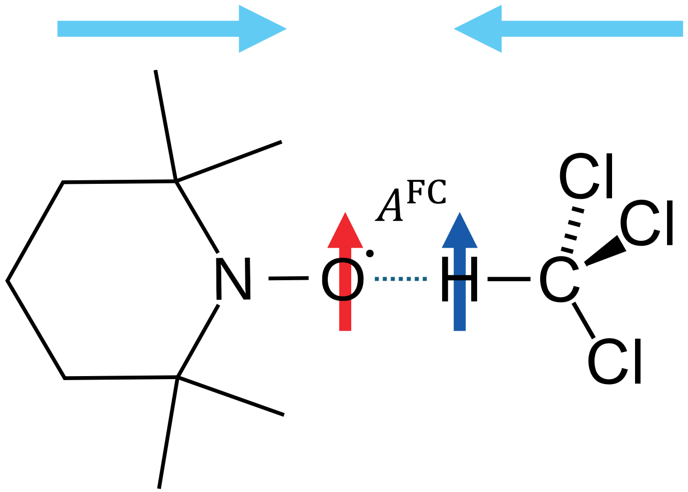
T. R. Carver and C. P. Slichter, *Phys. Rev.*, 1953, **92**, 212–213.

Hyperfine fluctuations in solution

e.g. TEMPO in chloroform



Dipolar coupling
Modulated by relative molecular diffusion



Scalar coupling
Modulated by molecular collisions

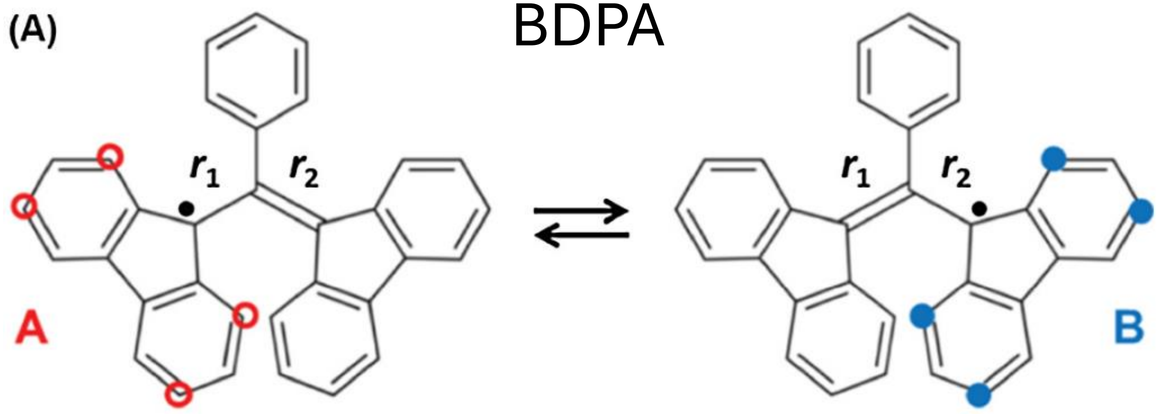
- Both FC and dipolar. ^{1}H only works at low field. ^{13}C has less dipolar so works at 9.4 T

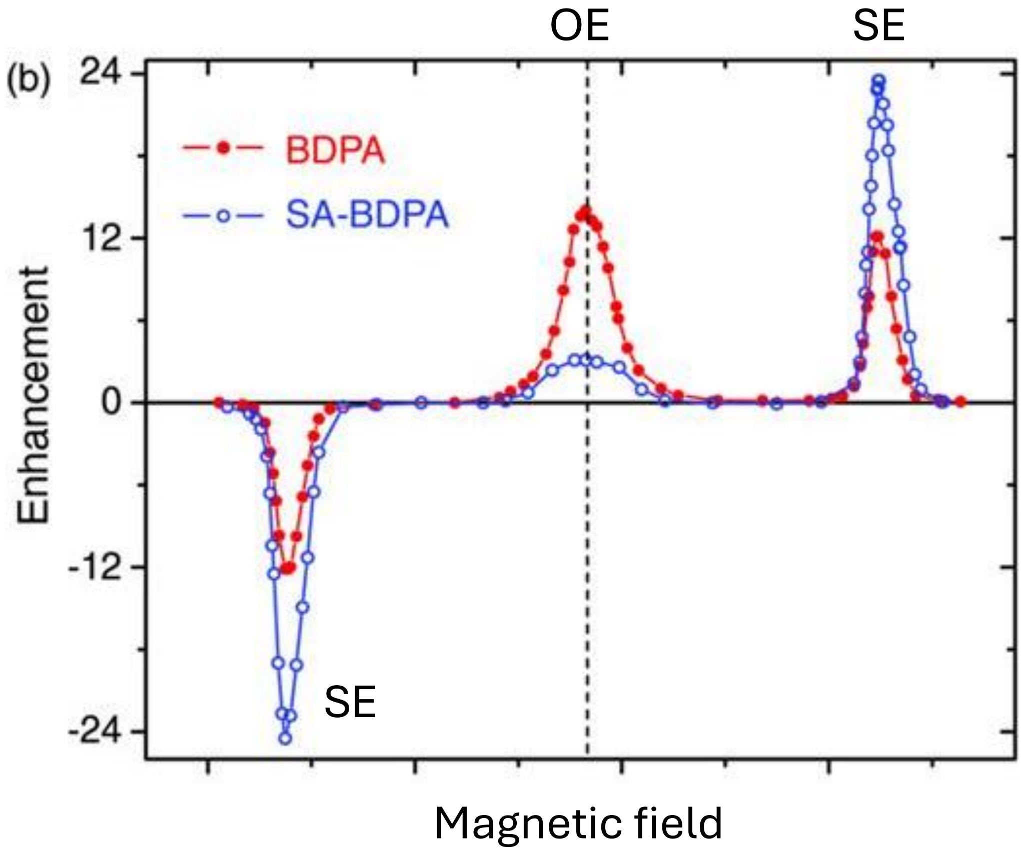
Liu, Bennati et al., *Nat. Chem.*, 2017

Overhauser Effect in Insulating Solids

- OE reported in solid samples of BDPA in polystyrene
- Spectral density ascribed to fluctuations of radical
- No diffusion, dominated by Fermi contact, works at high field

BDPA

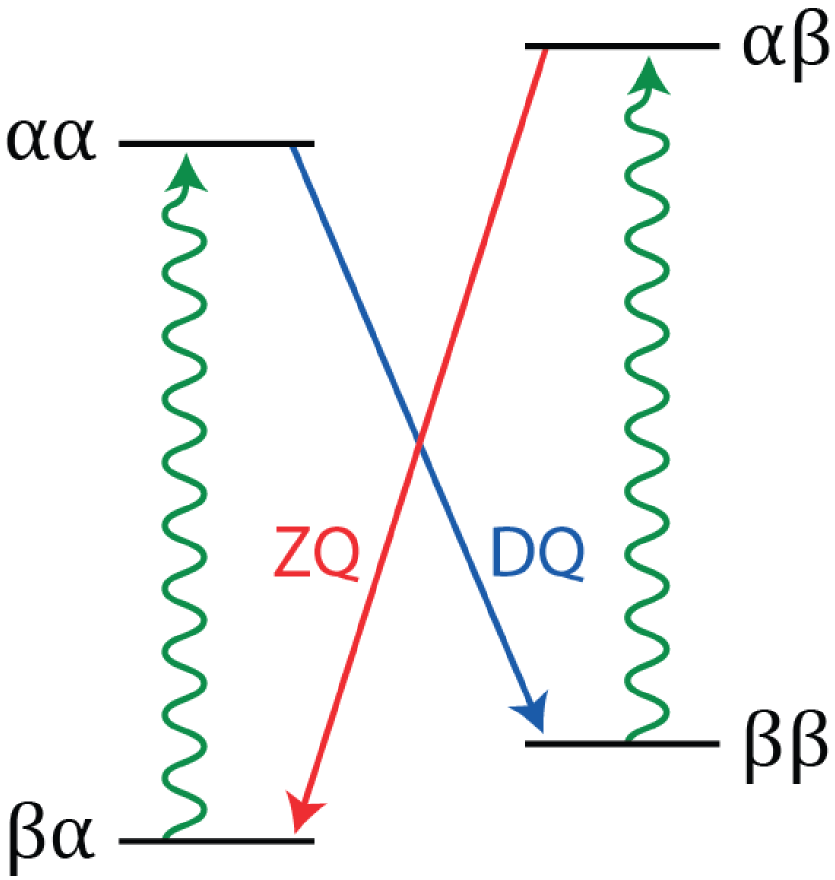




Can et al., *J. Chem. Phys.*, 2014
Pylaeva et al., *J. Phys. Chem. Lett.*, 2017

Overhauser Effect Summary

- Electron resonance saturated
- Cross relaxation with nucleus generates hyperpolarisation
- Sign of enhancement depends on ZQ vs DQ rate
- Mainly used in liquids
- Only works at low field (<1 T) unless dominated by scalar coupling



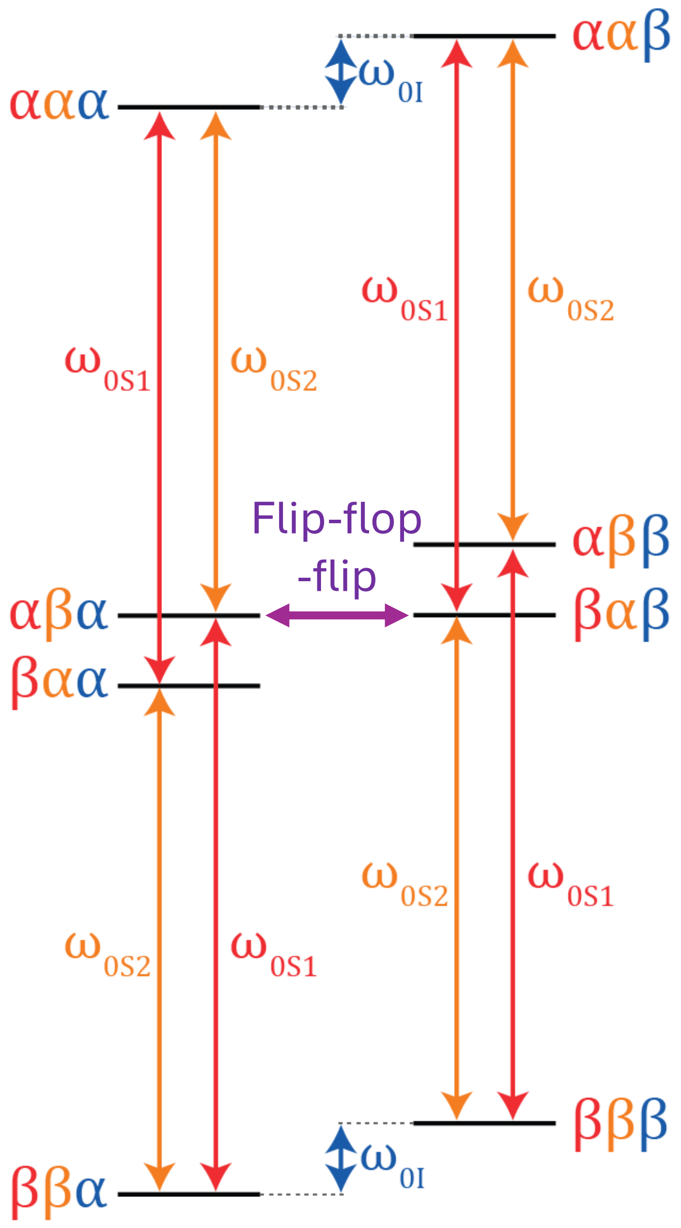
Questions?

Cross effect

Alexander Kessenikh

Cross Effect

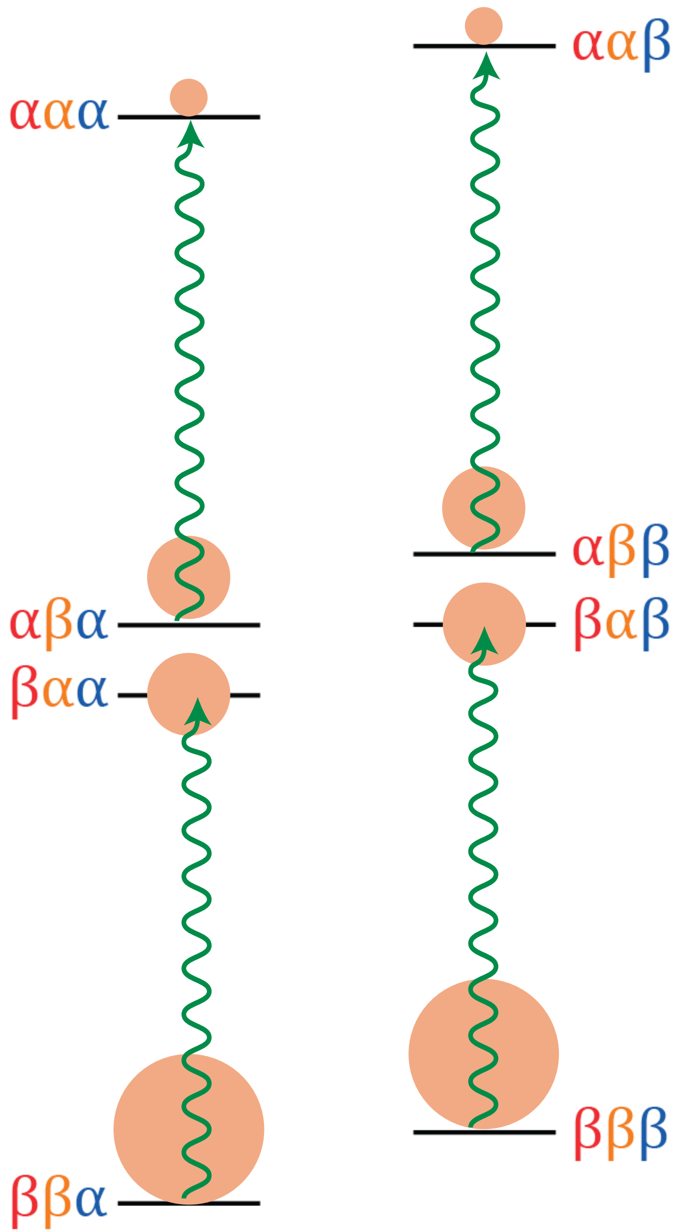
- Cross effect is a three-spin process
- Consider two coupled electrons, at least one of which is coupled to a nucleus
- Matching condition: $\omega_{0S1} - \omega_{0S2} = \omega_{0I}$
- Flip-flop-flip transitions conserve energy
- (Weakly allowed due to state mixing. Requires anisotropic e-e coupling and e-n coupling. Like SE, but more complicated maths!)



Thankamony et al., Prog. Nucl. Magn. Reson. Spectrosc., 2017

Cross Effect

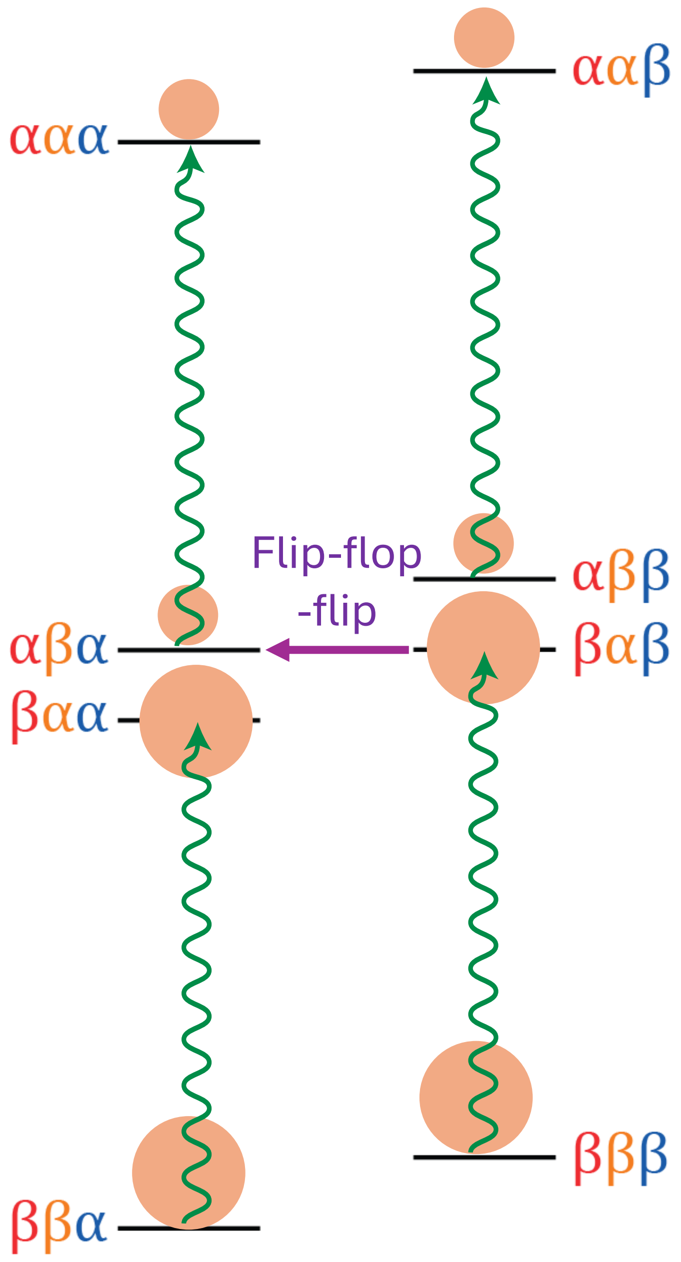
- Saturate one electron with microwaves (shown for S_2)



Thankamony et al., Prog. Nucl. Magn. Reson. Spectrosc., 2017

Cross Effect

- Saturate one electron with microwaves (shown for S_2)
- The population of the degenerate levels are no longer equal, so the flip-flop-flip rates are unequal, generating nuclear hyperpolarisation
- Define $\omega_{0S1} > \omega_{0S2}$
- $\omega_{\mu w} = \omega_{0S2}, \quad |\beta\alpha\beta\rangle \rightarrow |\alpha\beta\alpha\rangle$
  Positive enhancement



Thankamony et al., *Prog. Nucl. Magn. Reson. Spectrosc.*, 2017

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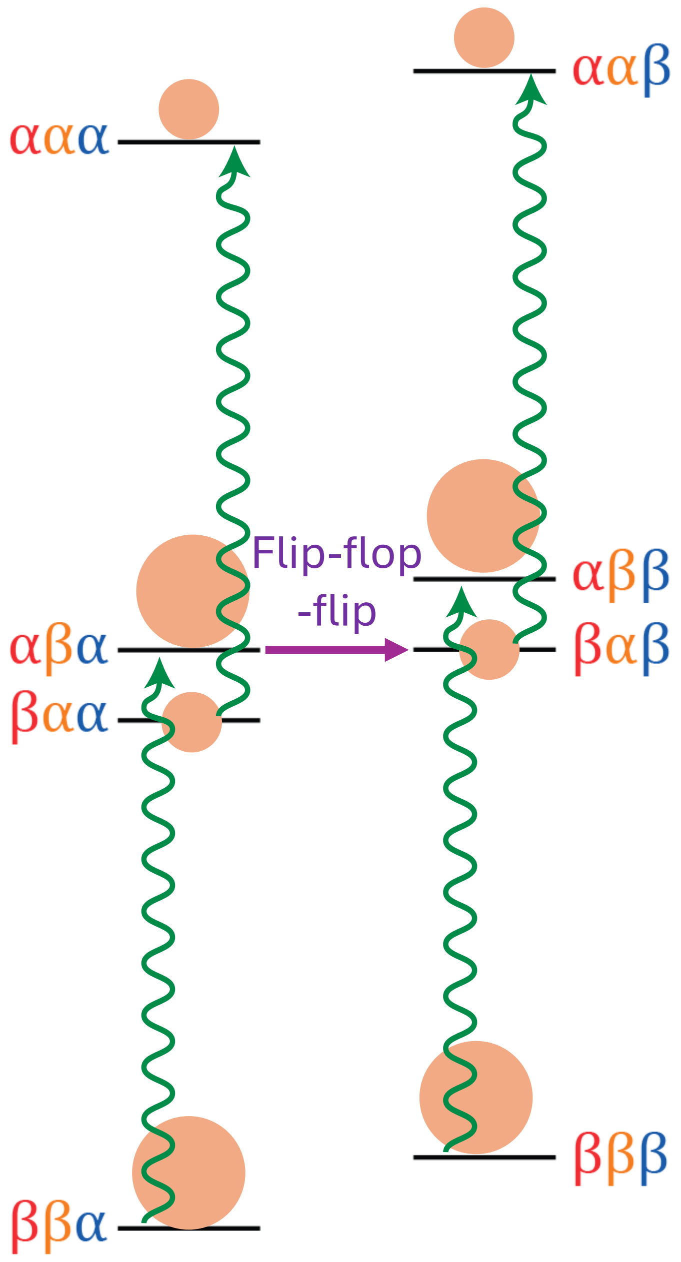
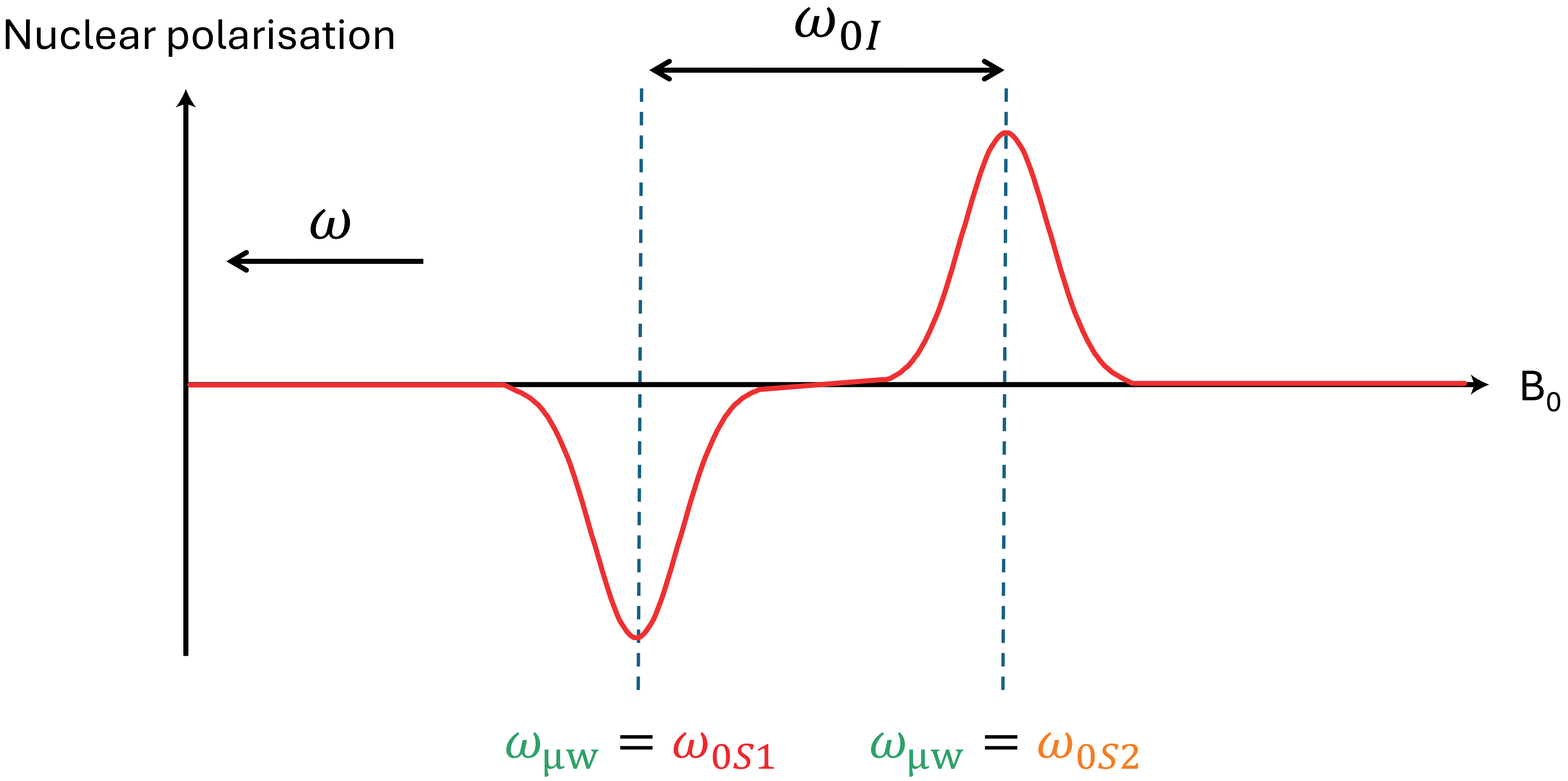
  Positive enhancement
- $\omega_{\mu w} = \omega_{0S1}, \quad |\alpha\beta\alpha\rangle \rightarrow |\beta\alpha\beta\rangle$
  Negative enhancement



Thankamony et al., *Prog. Nucl. Magn. Reson. Spectrosc.*, 2017

Cross Effect Field Profile

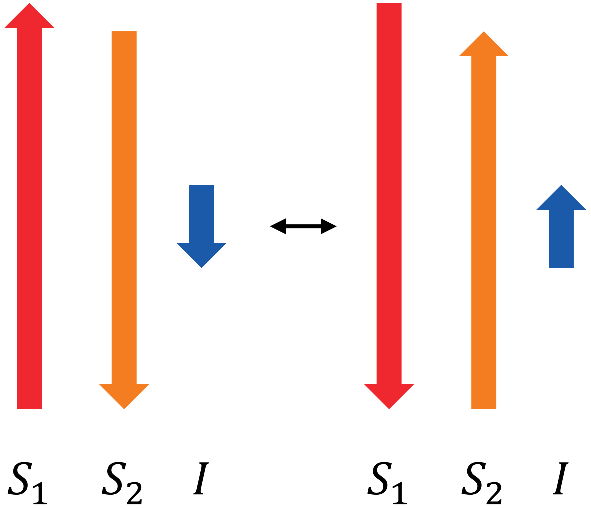


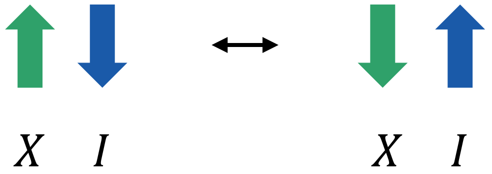
Matching condition: $\omega_{0S1} - \omega_{0S2} = \omega_{0I}$

So lobes are separated by ω_{0I}

Cross effect with a fictitious spin

- Can consider a fictitious spin $X = S_1 - S_2$
- $E_X = E_{S1} - E_{S2} = E_I$ (cross-effect condition)
- Cross effect = flip-flops between X and I
- Polarisation $P_X = P_{S1} - P_{S2}$
- Thermal equilibrium, P_X given by Boltzmann. $E_X = E_I$, so $P_X = P_I$
- If S_2 is saturated, $P_X = P_{S1}$, i.e. large polarisation
- Cross effect transfers polarisation from X to I

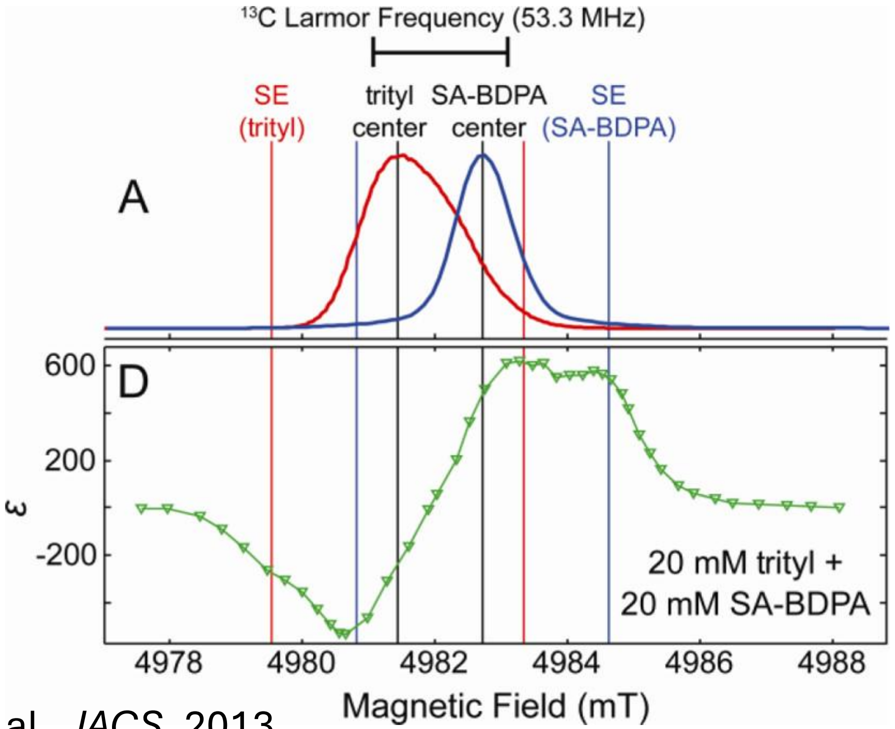




How to achieve the matching condition?

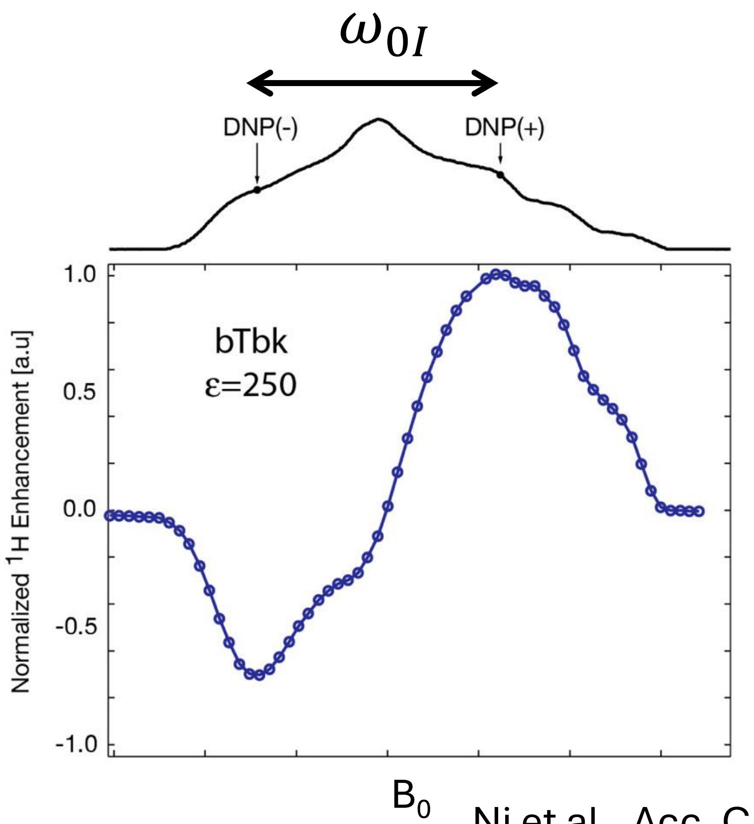
$$\omega_{0S1} - \omega_{0S2} = \omega_{0I}$$

- Two narrow line radicals that happen to match for a certain nucleus
- Difficult to achieve in practice!



Michaelis et al., *JACS*, 2013

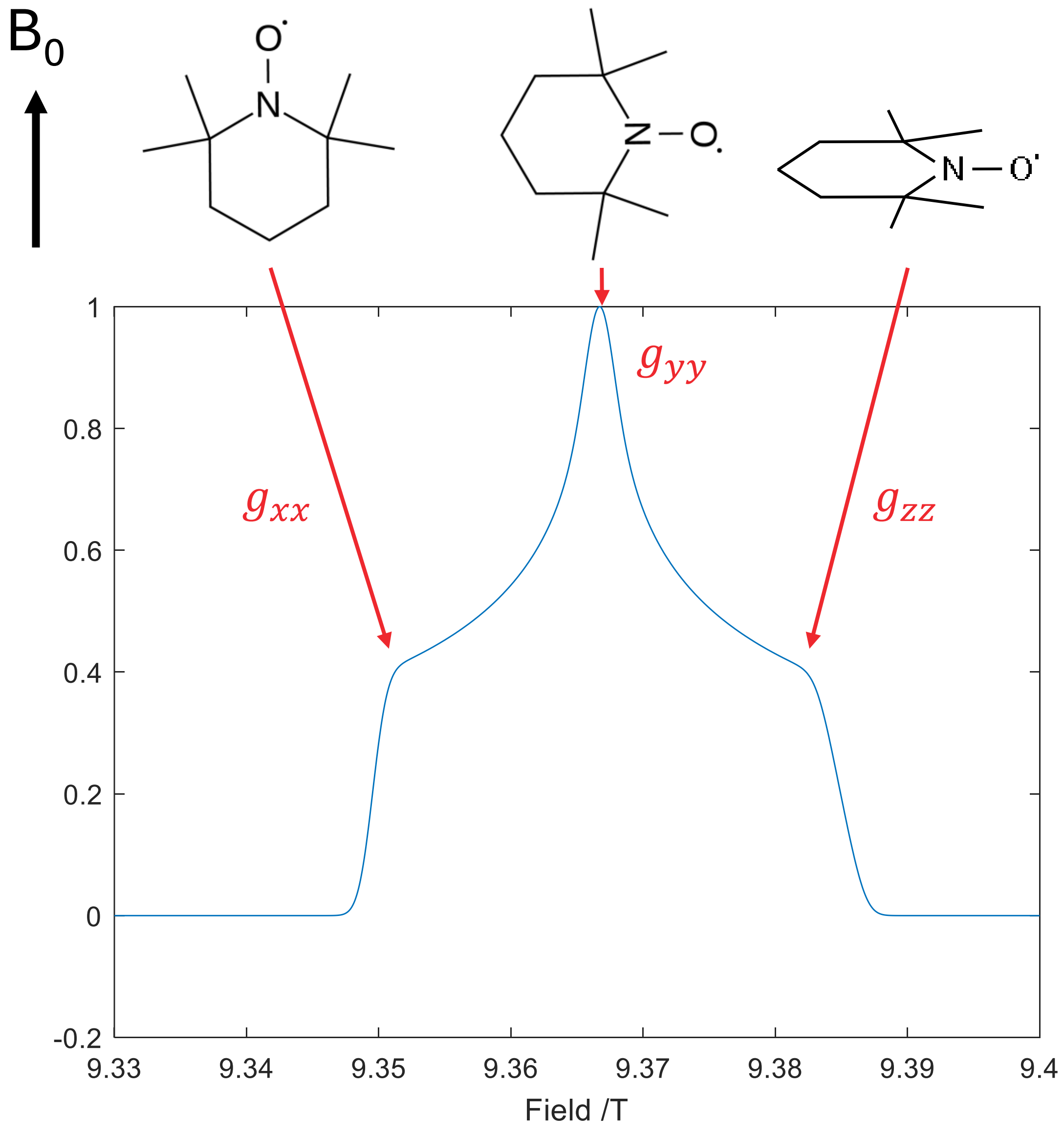
- A broad-line radical where the anisotropy is greater than the nuclear Larmor frequency



Ni et al., Acc. Chem. Res., 2013

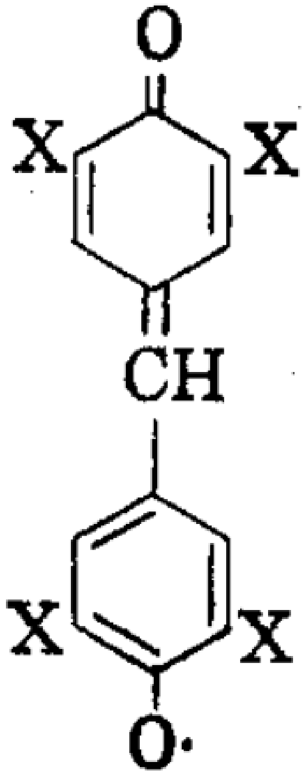
g Anisotropy

- For broadline radicals, electron g value depends on orientation
- Analogous to CSA in NMR
- Radicals with different orientations in the sample have different EPR frequencies



Cross effect with monoradicals

- Cross effect was originally observed for high concentrations (5%) of monoradicals with g-anisotropy dissolved in a polystyrene glass
- Only works when two radicals with the right orientations so that $\omega_{0S1} - \omega_{0S2} = \omega_{0I}$ happen to be near each other
- This is unlikely, reducing the enhancement and requiring high concentrations!



Ley's radical

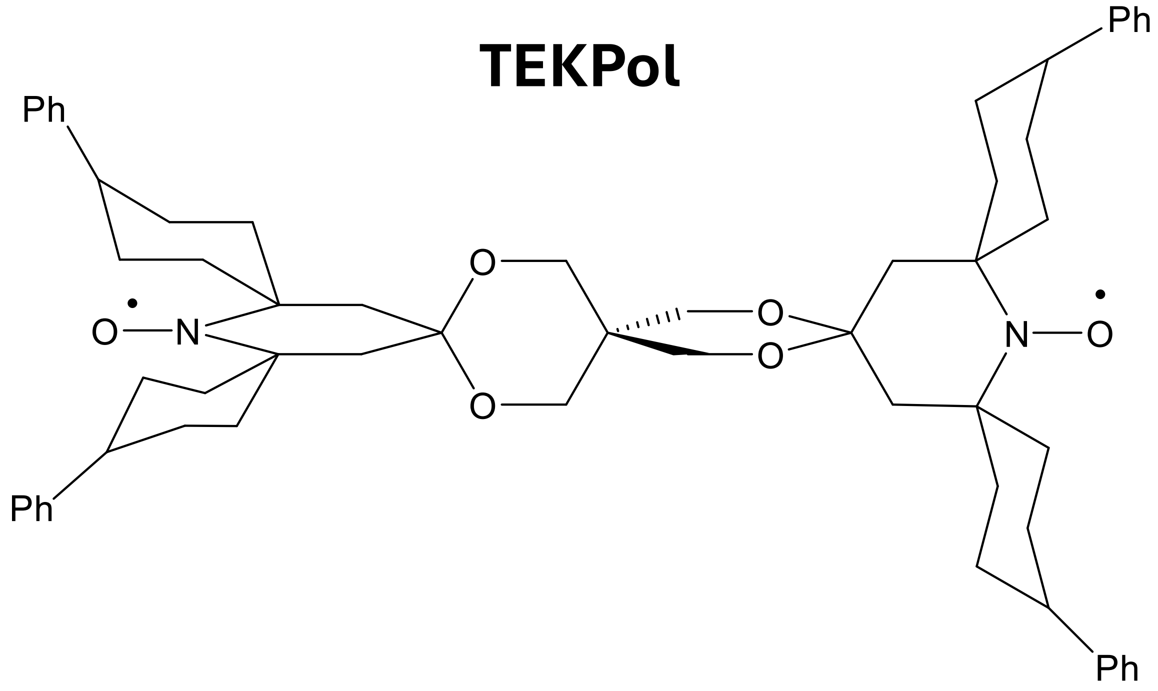
X= *tert*-butyl

Hwang and Hill, *Phys. Rev. Lett.* **18**, 110, 1967

Biradicals

- Tethered biradicals ensure that there are two electrons close together, even at low concentrations
- Designed so that the g-tensors are ~orthogonal so the electrons have different frequencies
- Optimised e-e distance to give large dipolar coupling, without too fast relaxation
- Bulky groups give long $T_{1\mathrm{e}}$ and $T_{2\mathrm{e}}$ to increase electron saturation
- Enhancement by factor $\varepsilon_H \approx 200$

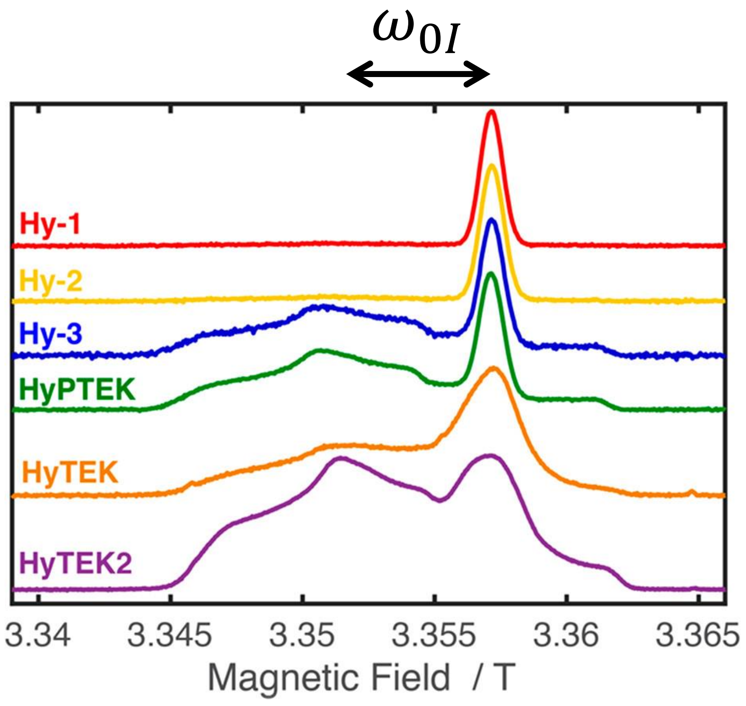
TEKPol

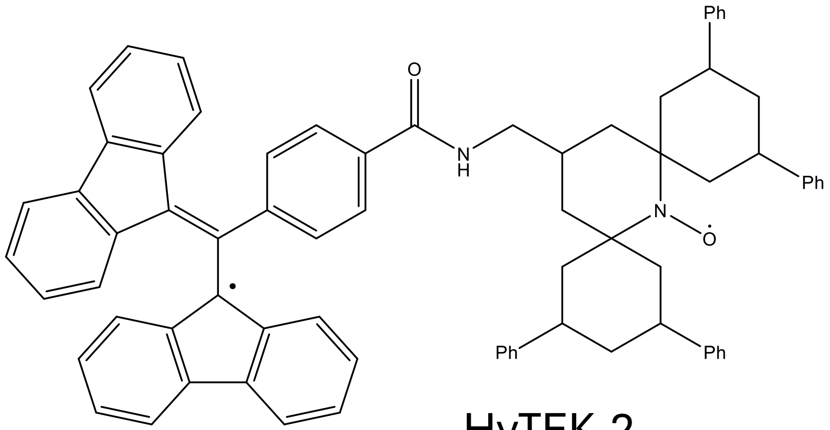


Hu et al., *JACS*, 2004. Zagdoun et al., *JACS*, 2013

Hybrid biradicals

- Bi-nitroxides were optimised at 9.4 T (400 MHz)
- EPR linewidth ∝ B_0 when dominated by g anisotropy
- At higher field, becomes harder to saturate, reducing enhancement ($\varepsilon \approx$ 20 at 900 MHz)
- Hybrid biradicals have a narrow line radical tethered to a wideline radical
- Narrow line can be easily saturated
- Narrow – wide = ω_{0I}
- $\varepsilon \approx$ 200 at 900 MHz





HyTEK-2

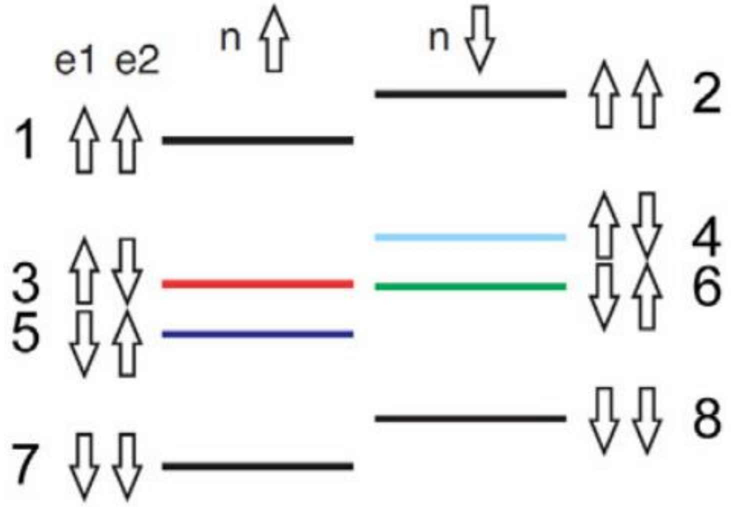
Wisser et al., *JACS*, 2018. Berruyer et al., *J. Phys. Chem. Lett.*, 2020

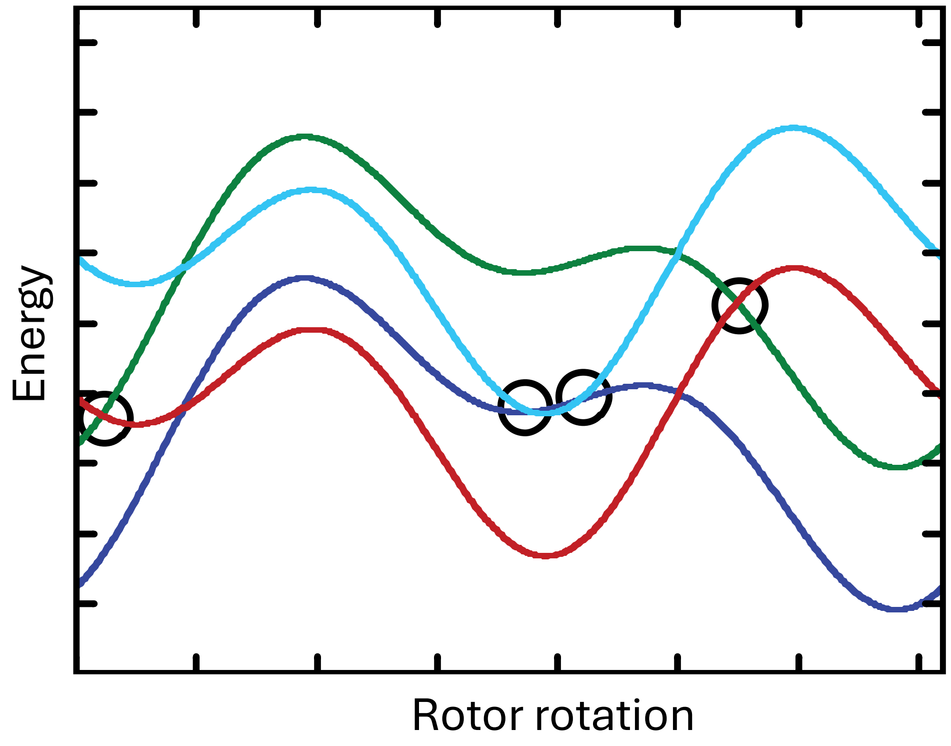
MAS DNP

What about the MAS?

Cross Effect under MAS

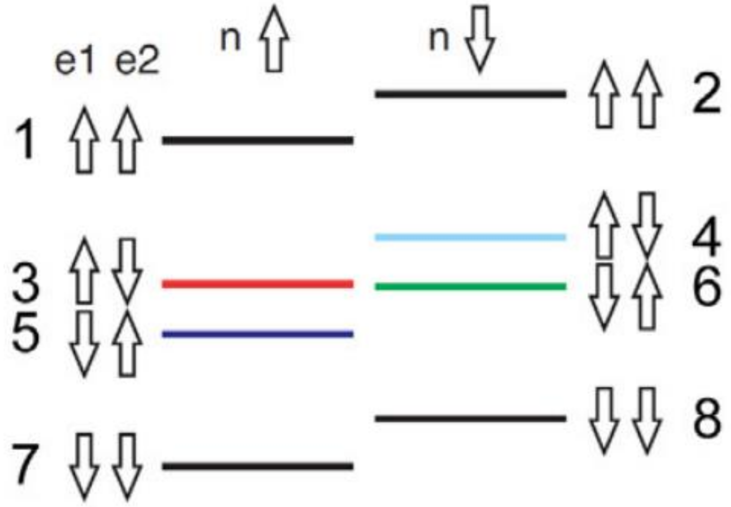
- Electron frequencies are orientation dependent
- Under MAS, they become time dependent
- At certain orientations, the levels have the same energy
- Called a level crossing





Thurber and Tycko, *J. Chem. Phys.*, 2012
Thankamony et al., *Prog. Nucl. Magn. Reson. Spectrosc.*, 2017

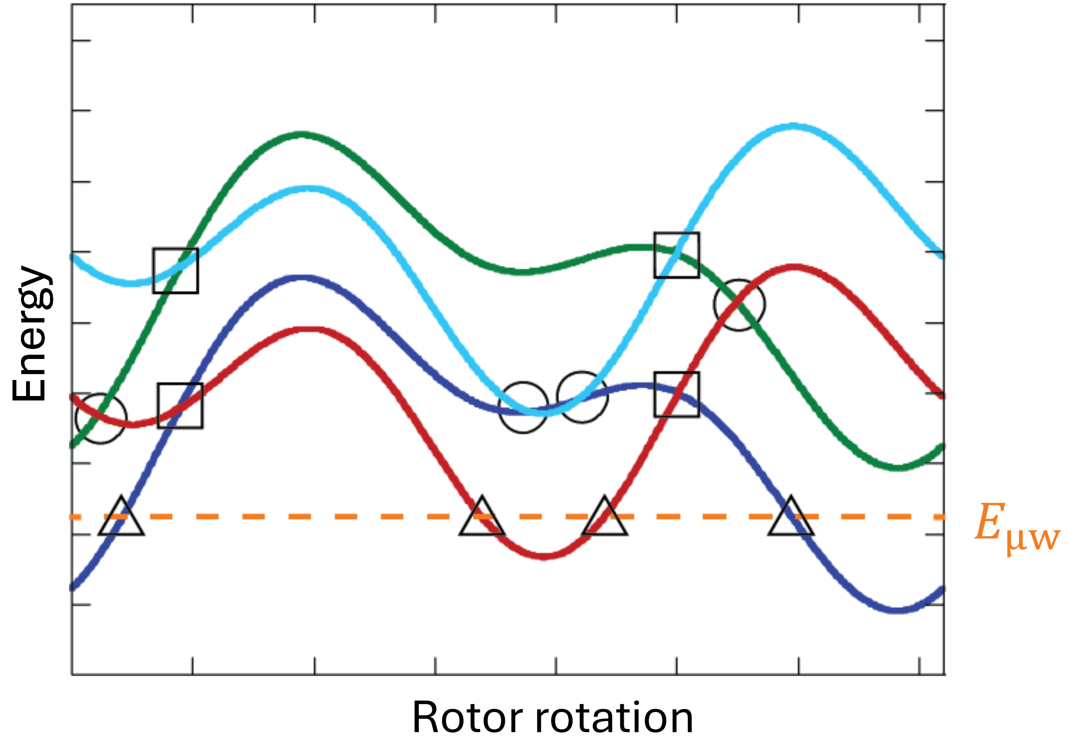
Types of Level Crossing



○ • Cross effect flip-flop-flips (circles): $|\beta\alpha\beta\rangle \leftrightarrow |\alpha\beta\alpha\rangle$
Generate nuclear polarisation

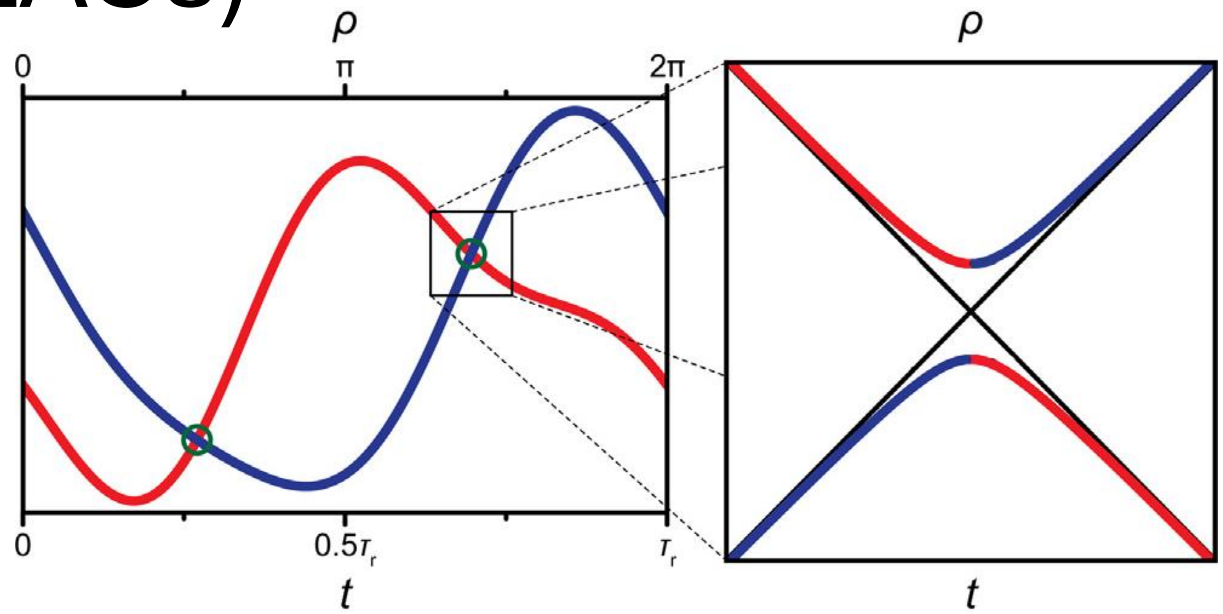
□ • Electron-electron flip-flop (squares): $|\beta\alpha\rangle \leftrightarrow |\alpha\beta\rangle$
Exchange electron saturation

△ • Microwave-driven electron spin flips (triangles)
$|\alpha\rangle \leftrightarrow |\beta\rangle$ and $|\alpha\rangle \leftrightarrow |\beta\rangle$
Saturate the electron



Level anti crossings (LACs)

- Off-diagonal elements cause state mixing when the energy difference is small enough

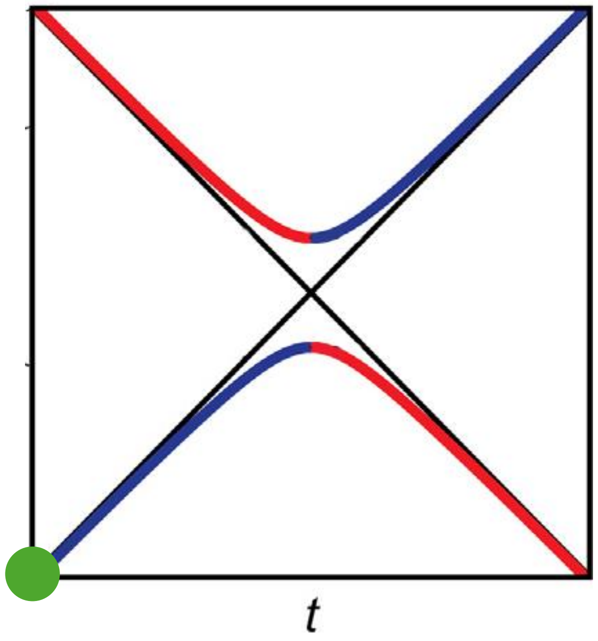


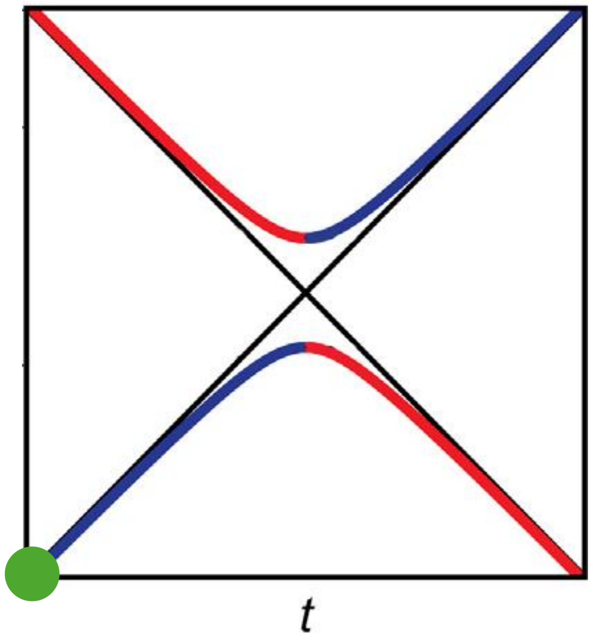
- $\hat{H} = \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix}$ has eigenstates with energies E_1 and E_2
- $\hat{H} = \begin{pmatrix} E_1 & W \\ W & E_2 \end{pmatrix}$ has energies $E = \frac{1}{2}(E_1 + E_2) \pm \frac{1}{2}\sqrt{(E_1 - E_2)^2 + 4W^2}$
- When W and $(E_1 - E_2)$ are comparable, in vicinity of crossing, the levels repel
- Known as a level anti-crossing or avoided level crossing

What happens at a LAC?

Fast Passage

Slow Passage





Stays in the same unperturbed state

Non-adiabatic

Follows the eigenstates

Adiabatic

How fast or slow?

- Landau-Zener equation:
- Probability of changing state (adiabatic passage),

$$P = 1 - \exp\left(-\frac{2\pi W^2}{d\Delta E/dt}\right)$$

- High probability for large coupling (W) and slow transit (small $\frac{d\Delta E}{dt}$)

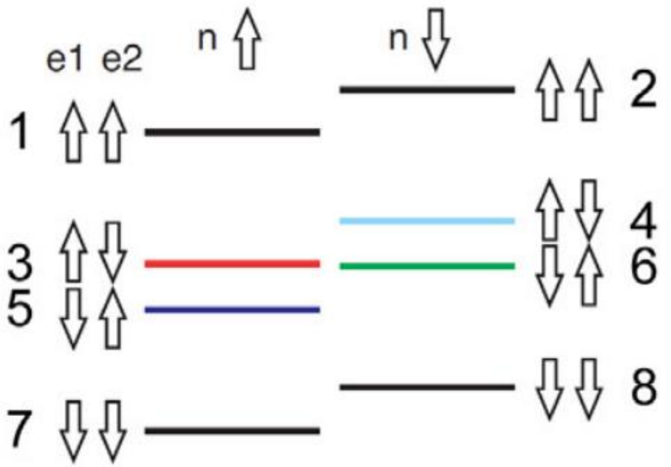
Adiabaticity of crossings

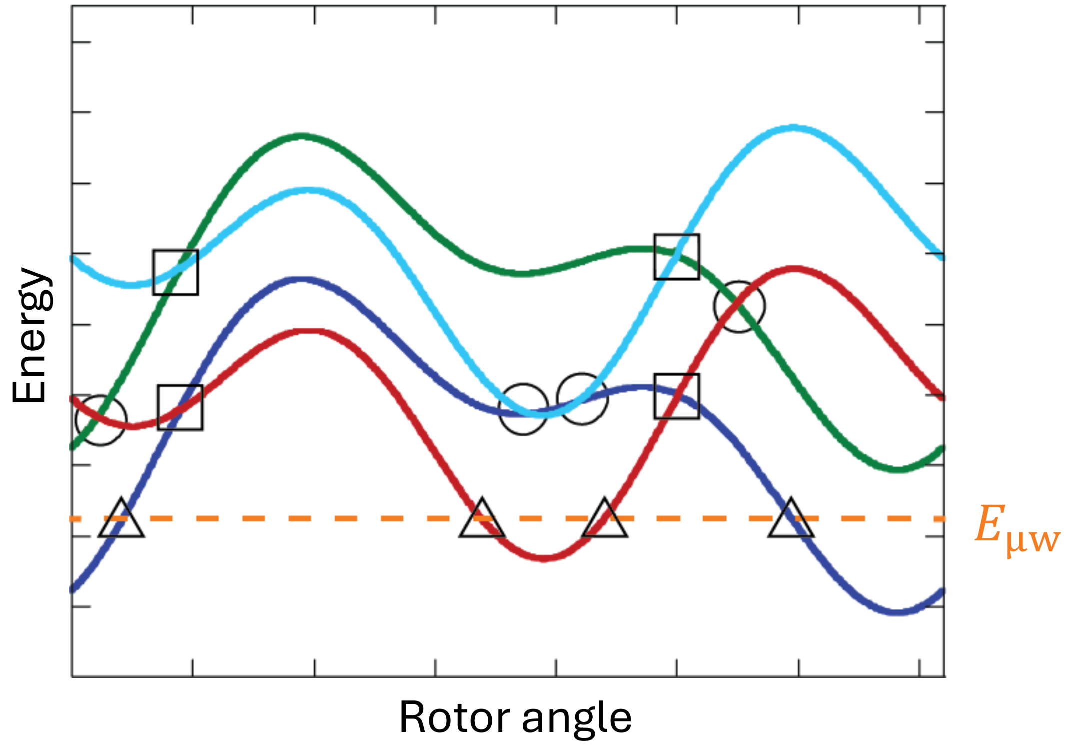
△

- Microwave-driven spin flips: $P \sim 50\%$
- Allowed transitions, large W.
  The electron can be saturated quite easily over a few rotor periods

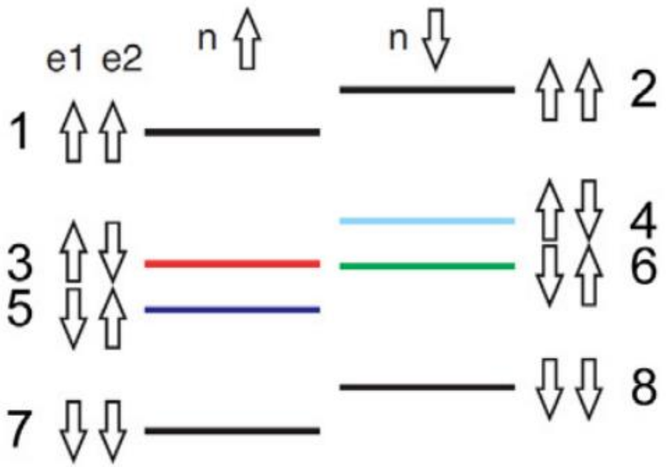
□

- Electron-electron flip-flops:
  $$P \approx 0.999999$$
- Strong e-e coupling, so electron saturation almost always transfers
- The saturated electron is always the lower (higher) energy electron, so the enhancement is always positive (negative) and doesn't cancel out.



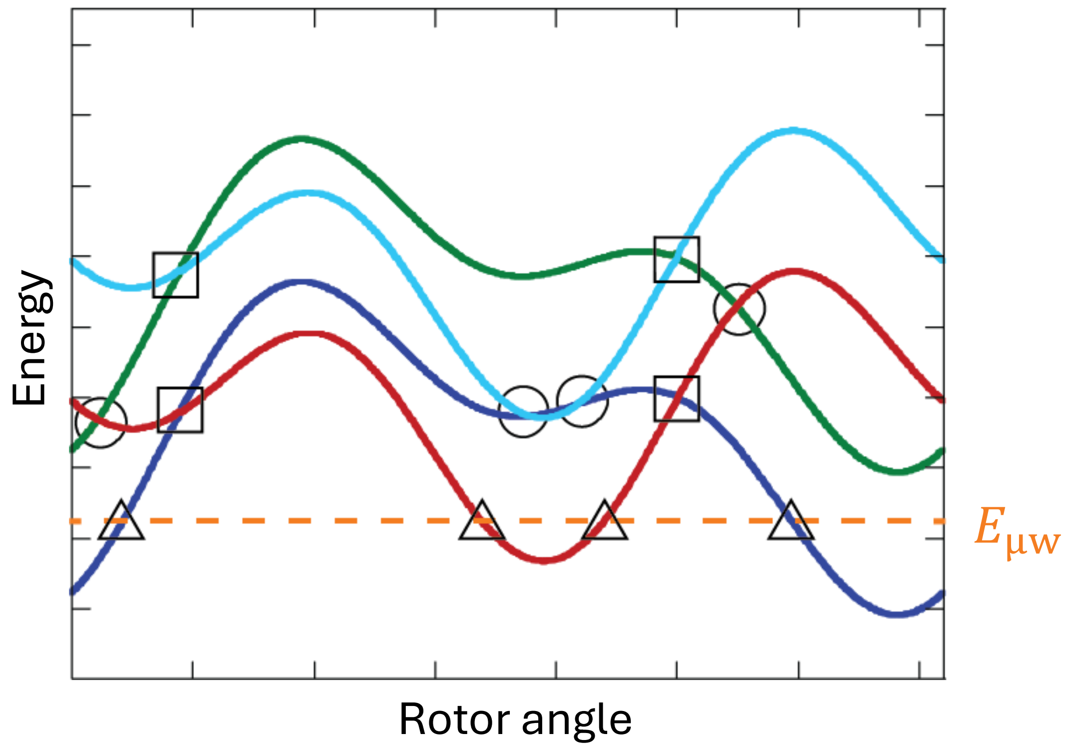


Adiabaticity of crossings



- Cross effect flip-flop-flips: $P \sim 0.1\%$
- Probability of cross effect transition is low
- Nuclear $T_1 \sim 1 - 10\ s = 10^3 - 10^4$ rotor periods
- Over many events, hyperpolarisation builds up

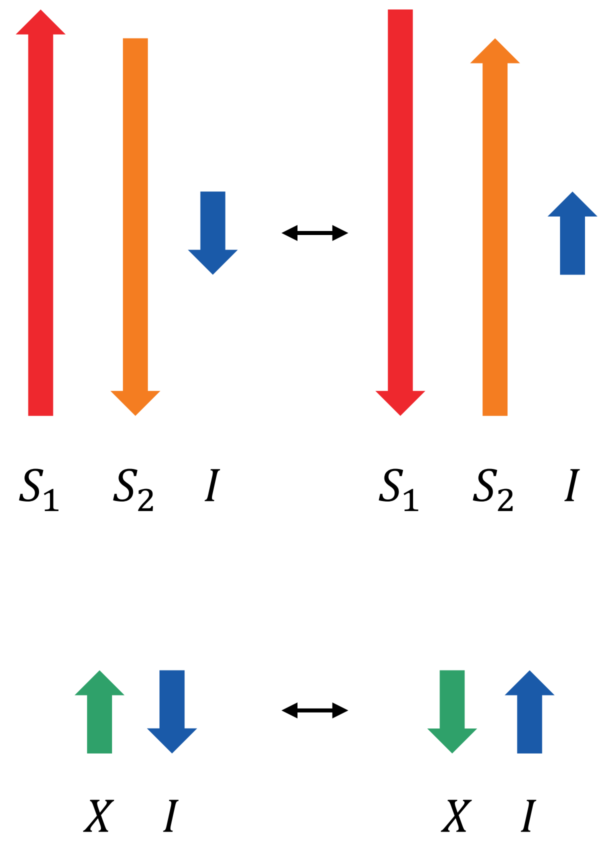
- Magic-angle spinning separates the electron-microwave and cross-effect events in time
- Conditions do not need to be simultaneously satisfied
- Many more orientations contribute to DNP, improving enhancements



Depolarisation

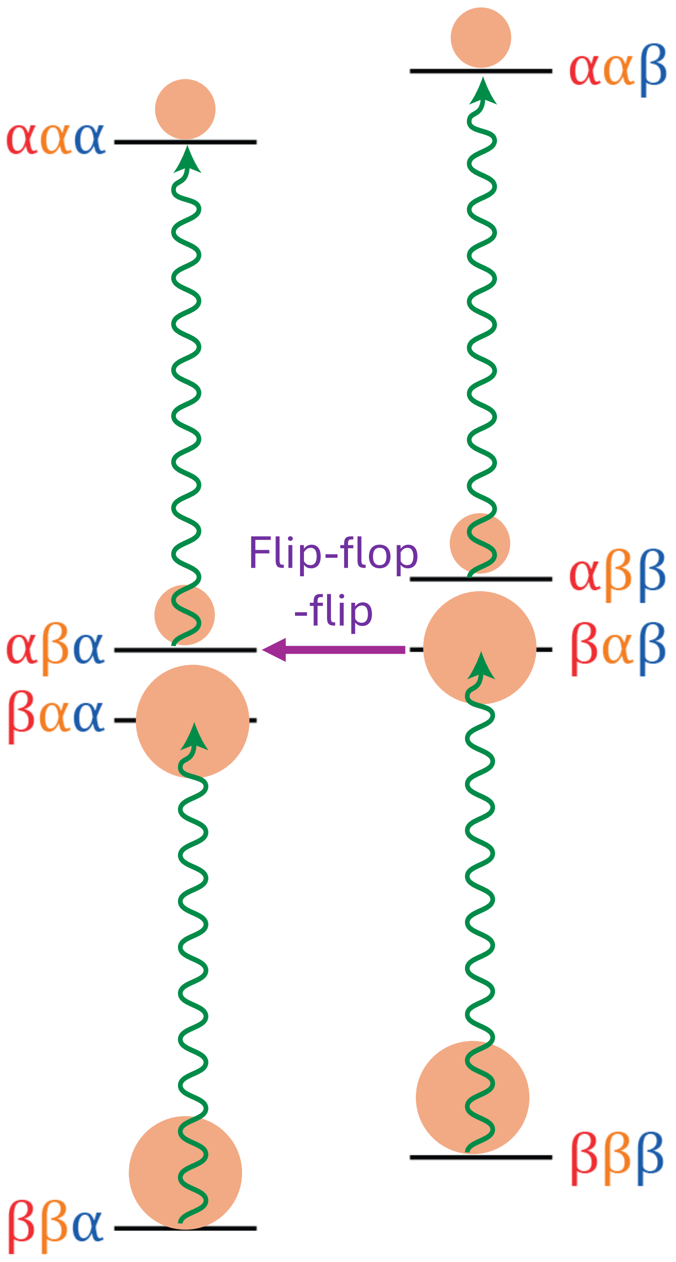
- In the absence of microwaves, the cross effect events still occur
- Electron-electron flip-flops also occur, acting to equalise the electron polarisations, reducing the difference polarisation $P_X = P_{S1} - P_{S2}$
- $P_X < P_I$, so cross effect *reduces* the nuclear polarisation
- This is called depolarisation
- Reduction in NMR signal under MAS, without microwaves
- Signal enhancement is overestimated vs thermal

$$\varepsilon = I_{\mathrm{ON}}/I_{\mathrm{OFF}}$$



Cross Effect Summary

- Two coupled electrons and a coupled nuclear spin
- One of the electrons is saturated by microwaves
- Cross-effect flip-flop-flips transfer electron difference polarisation to nucleus
- Typically biradicals with g-anisotropy are used to satisfy $\omega_{0S1} - \omega_{0S2} = \omega_{0I}$
- Under MAS, saturation and cross-effect events happen at different points of the rotor period, making CE more efficient

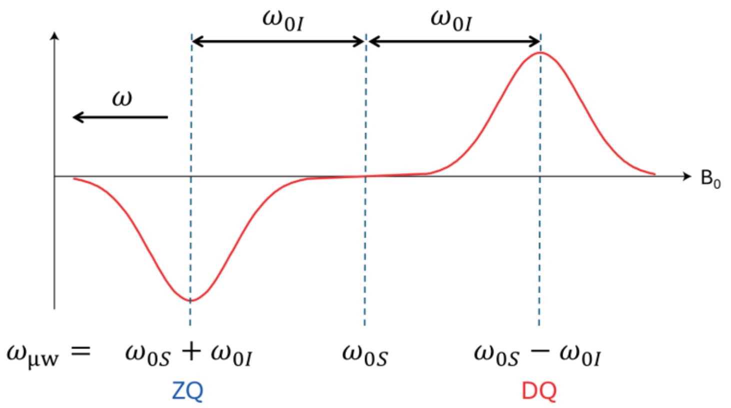


Questions?

Summary

Solid Effect

Drive forbidden e-n ZQ/DQ transitions



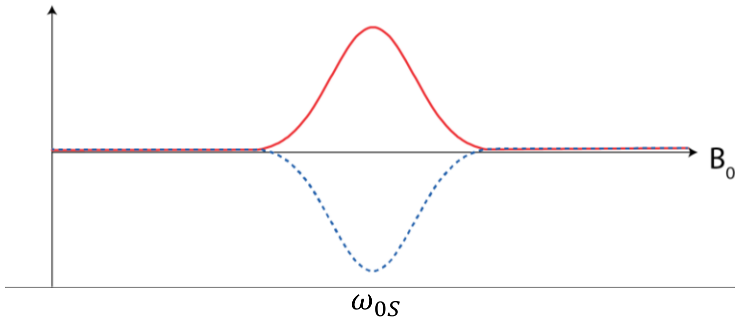
Narrow EPR line

Solid state

High μw power
(weakly allowed)

Overhauser Effect

Saturate SQ electron, e-n cross relaxation



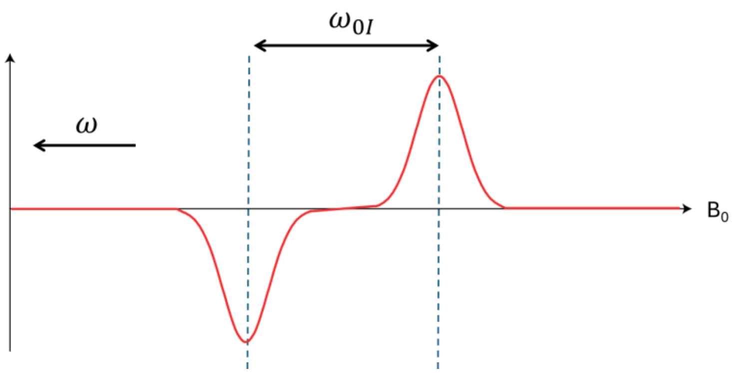
Narrow EPR line

Mainly liquid state

Lower μw power

Cross Effect

Saturate one electron, e-e-n flip-flop-flip transitions



Broad inhomogeneous EPR
(typically biradicals)

Solid state

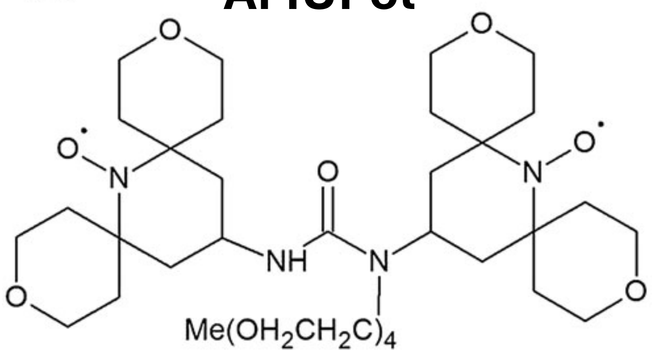
Medium μw power
(Broader EPR)

Running DNP experiments

DNP of Frozen Solutions

- Polarising agent (e.g. biradical) is dissolved in a glass-forming solvent (along with a target molecule)
- Flash frozen to form a glass with well dispersed radical
- Partially deuterated solvent so hyperpolarisation not diluted too much
- Radical concentration optimised to give enough polarisation sources, without strong radical-radical interactions

(a) **AMUPol**



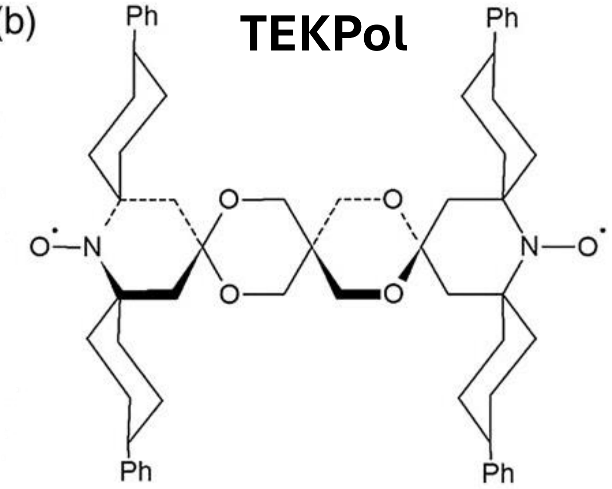
10 mM in 6:3:1 d_6-DMSO : D_2O : H_2O

6:3:1 d_8-glycerol : D_2O : H_2O

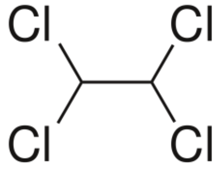
Sauvée et al., *Angew. Chem.*, 2013

10-20 M ^{1}H

(b) **TEKPol**



16 mM in TCE

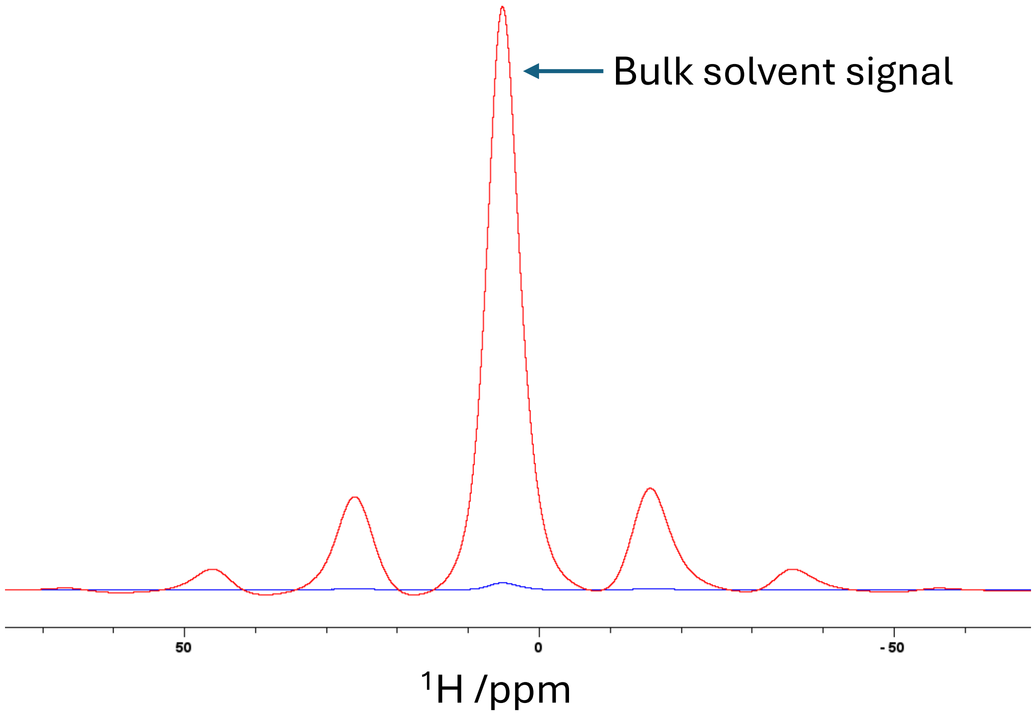


TCE

Zagdoun et al., *JACS*, 2013

DNP of Frozen Solutions

- Probe pre-cooled to 100 K
- Warm sample is (quickly) inserted to flash freeze
- For organic solvents (e.g. TCE), multiple insert/eject cycles to degas oxygen (paramagnetic relaxation sink)
- Turn on microwaves!
- ^1H-^1H spin diffusion relays hyperpolarisation away from radicals to enhance the bulk of the solvent (and dissolved target)



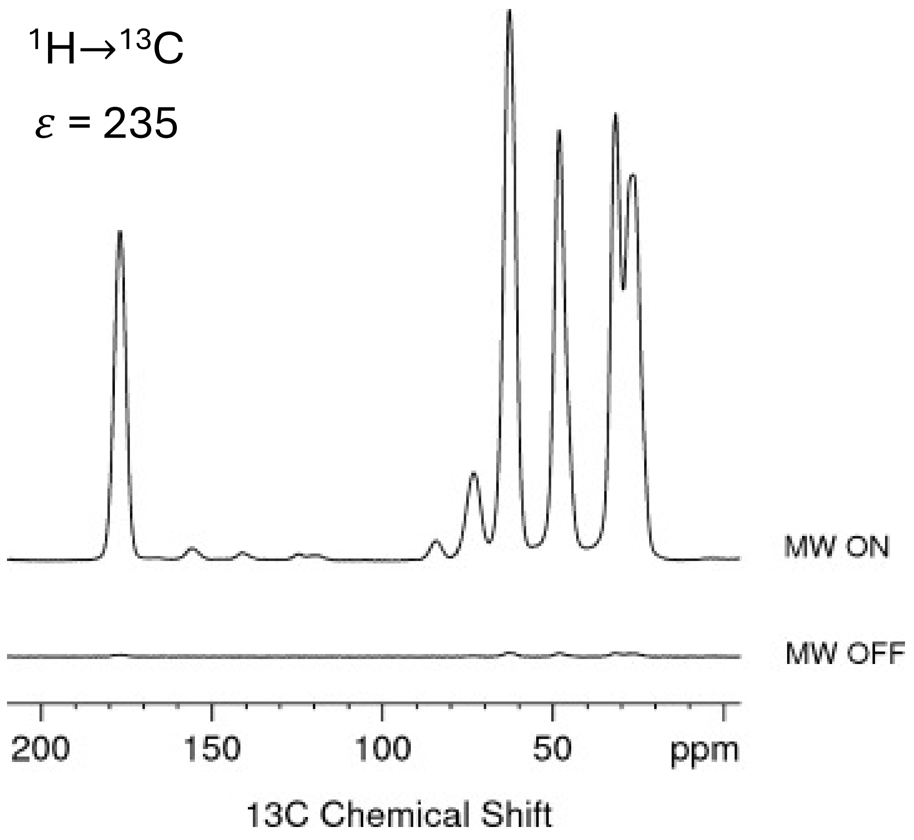
"Indirect DNP"

- After ^1H-^1H spin diffusion relays polarisation throughout the sample, cross polarisation transfers to the nucleus of interest
- Benefit from faster ^1H spin diffusion

$^1H \rightarrow ^{13}C$

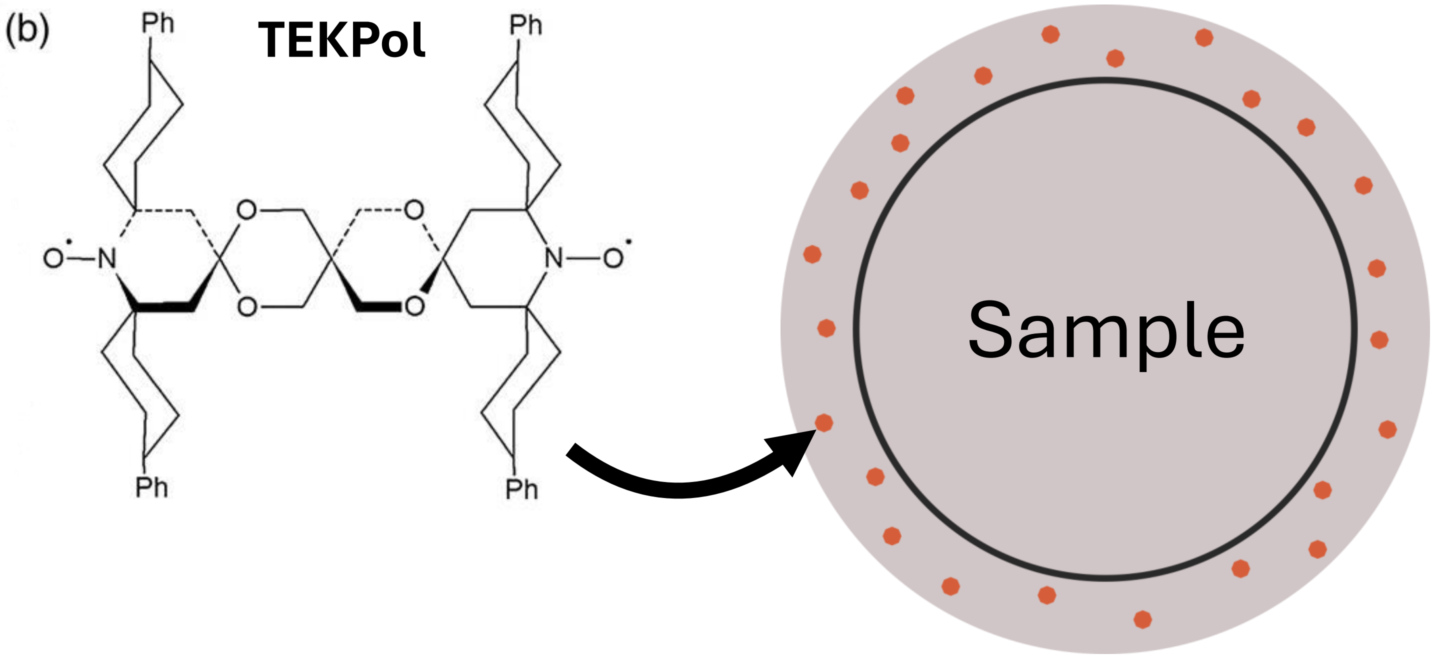
ε = 235

0.25 M Proline
10 mM AMUPol
6:3:1 d_8-glycerol:D_2O:H_2O



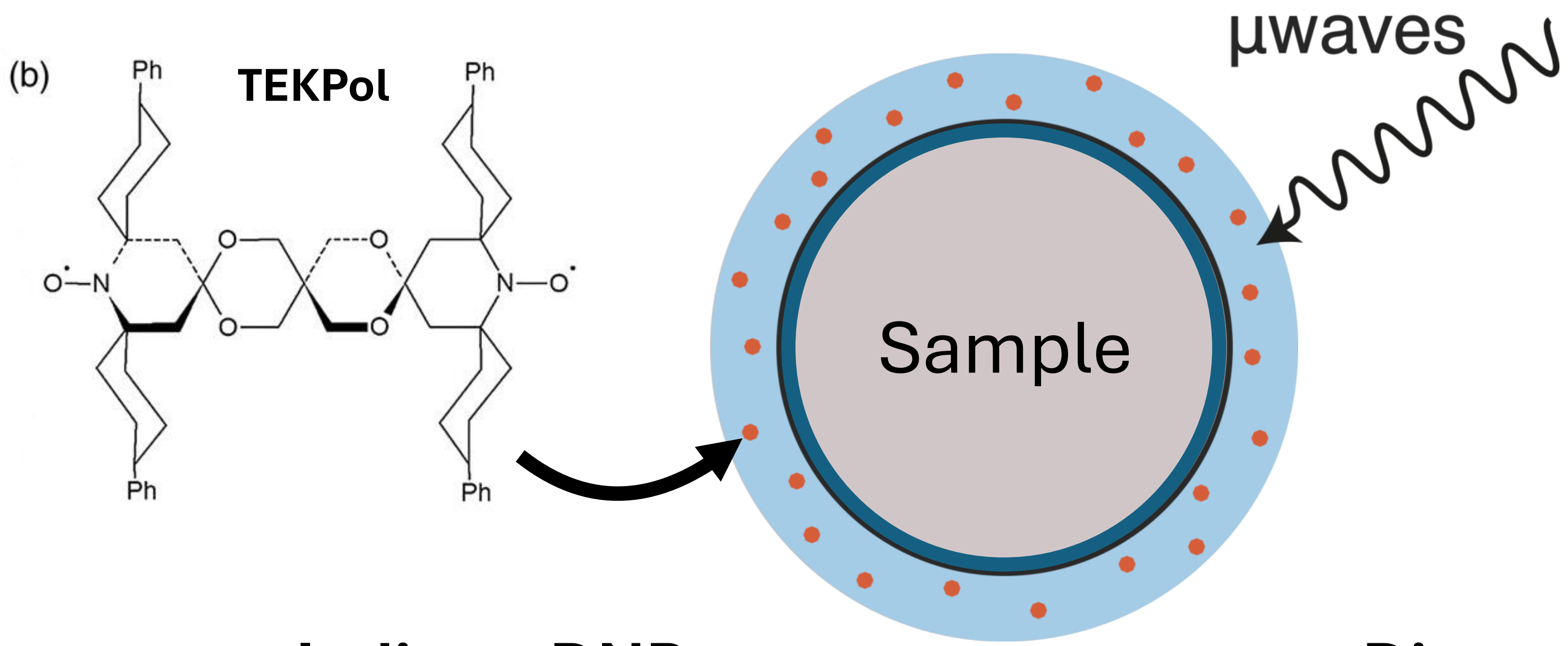
Sauvée et al., *Angew. Chem.*, 2013

Impregnation DNP



- Powdered sample is wetted with solution of polarising agents (just enough to coat the surfaces!)
- Can fill the pores of porous materials to access internal surfaces

Impregnation DNP



Indirect DNP

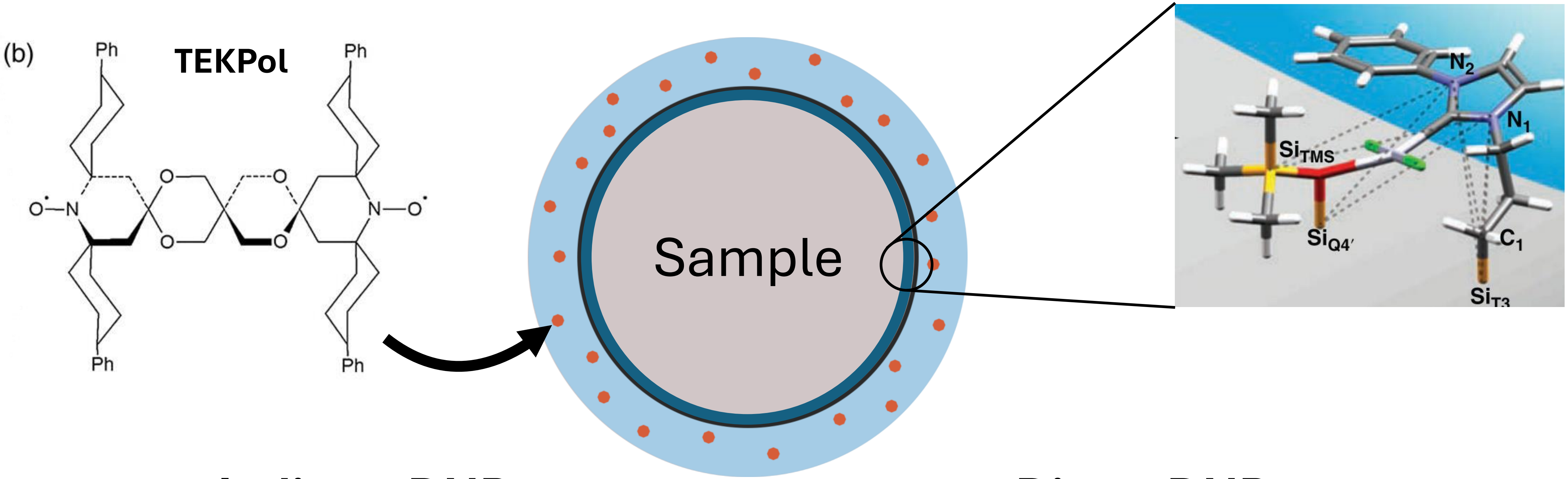
- Transfer from ^{1}H to nucleus of interest by CP
- Surface-selective if no ^{1}H in bulk

Direct DNP

- Nucleus directly polarised by DNP
- Surface-selective due to slow X spin diffusion

DNP Surface-Enhanced NMR (SENS)

Rossini et al., *Acc. Chem. Res.*, 2013



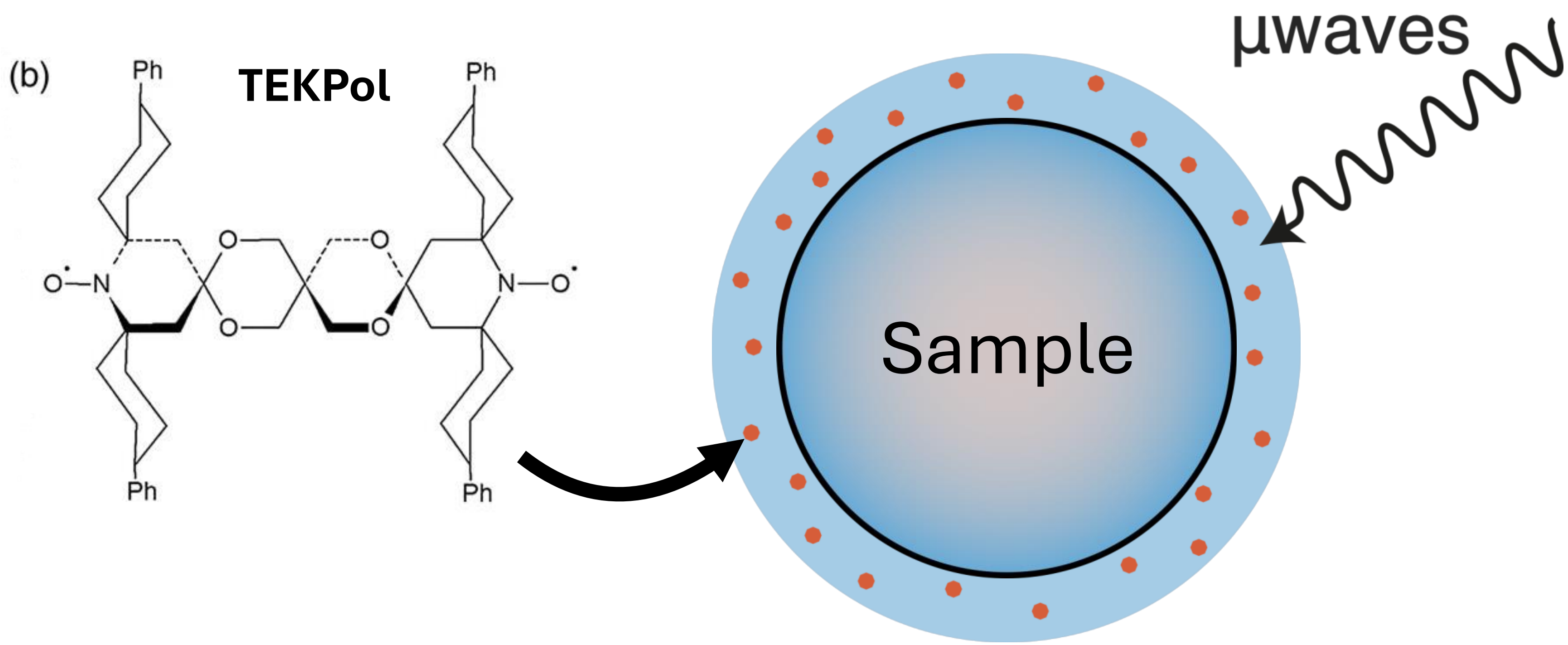
Indirect DNP

- Transfer from ^1H to nucleus of interest by CP
- Surface-selective if no ^1H in bulk

Direct DNP

- Nucleus directly polarised by DNP
- Surface-selective due to slow X spin diffusion

Relayed DNP



^{1}H in the sample

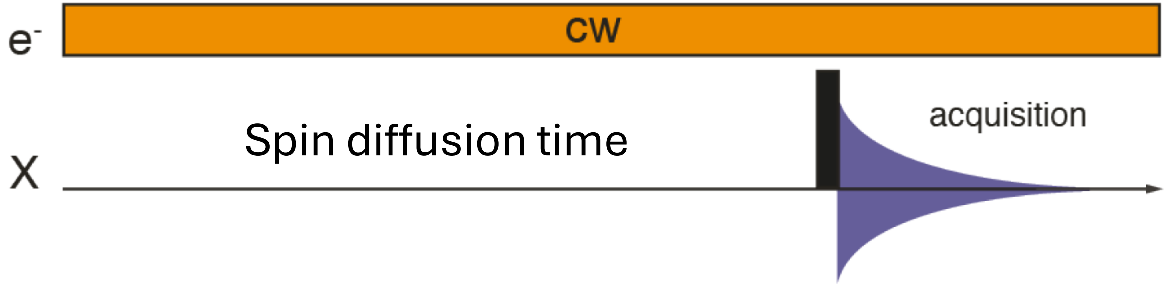
- Efficient ^{1}H spin diffusion into bulk
- ^{1}H→X CP to nucleus of interest

No ^{1}H in sample

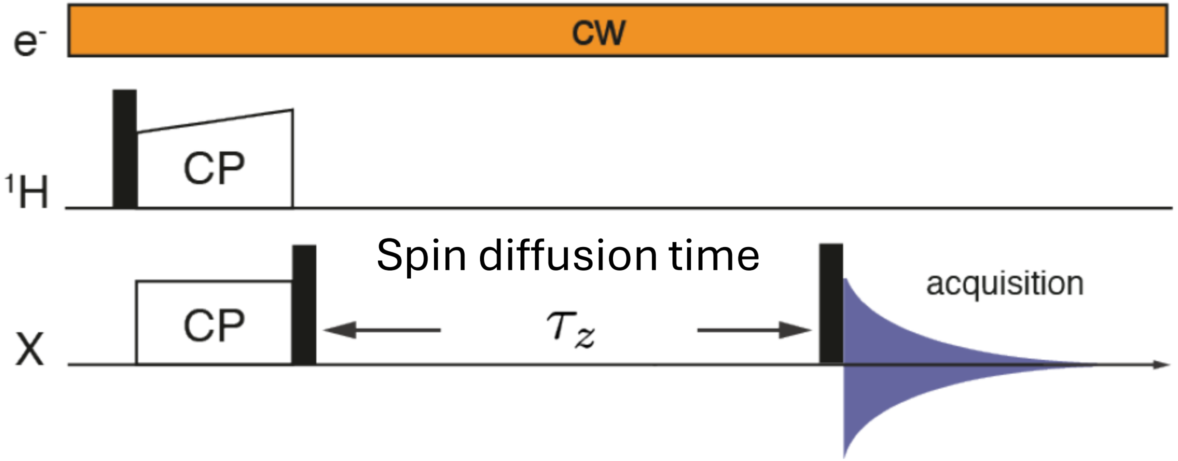
- Slow X spin diffusion
- Require long X T_1

Relayed DNP by X spin diffusion

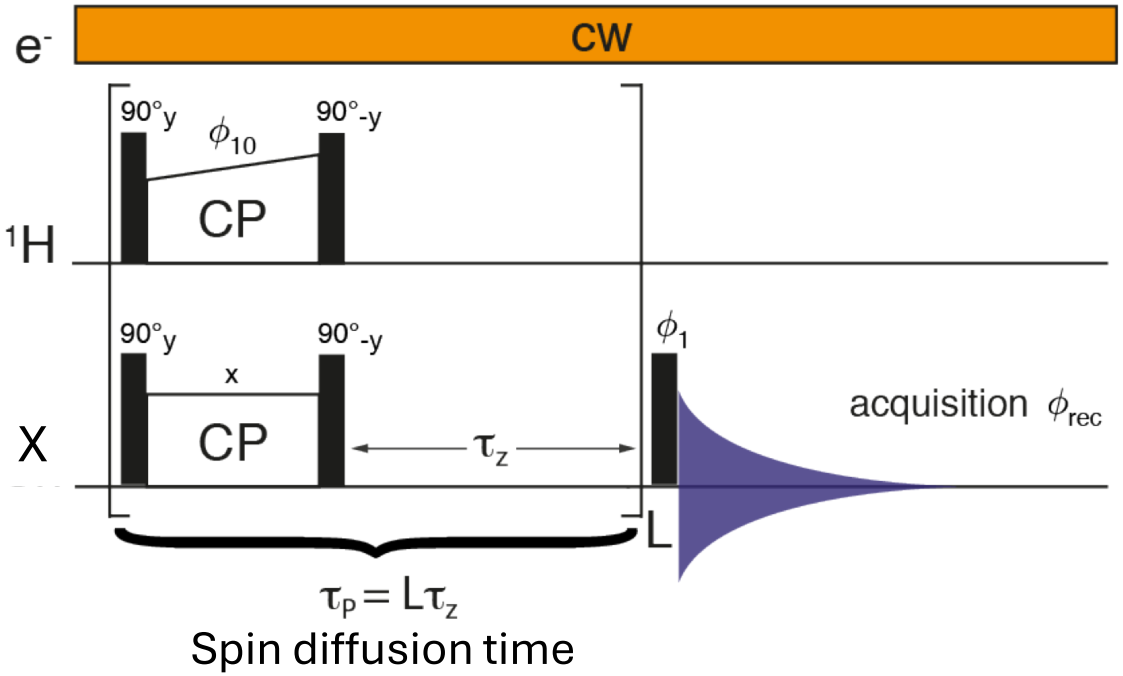
Direct DNP



Indirect DNP + Z-filter

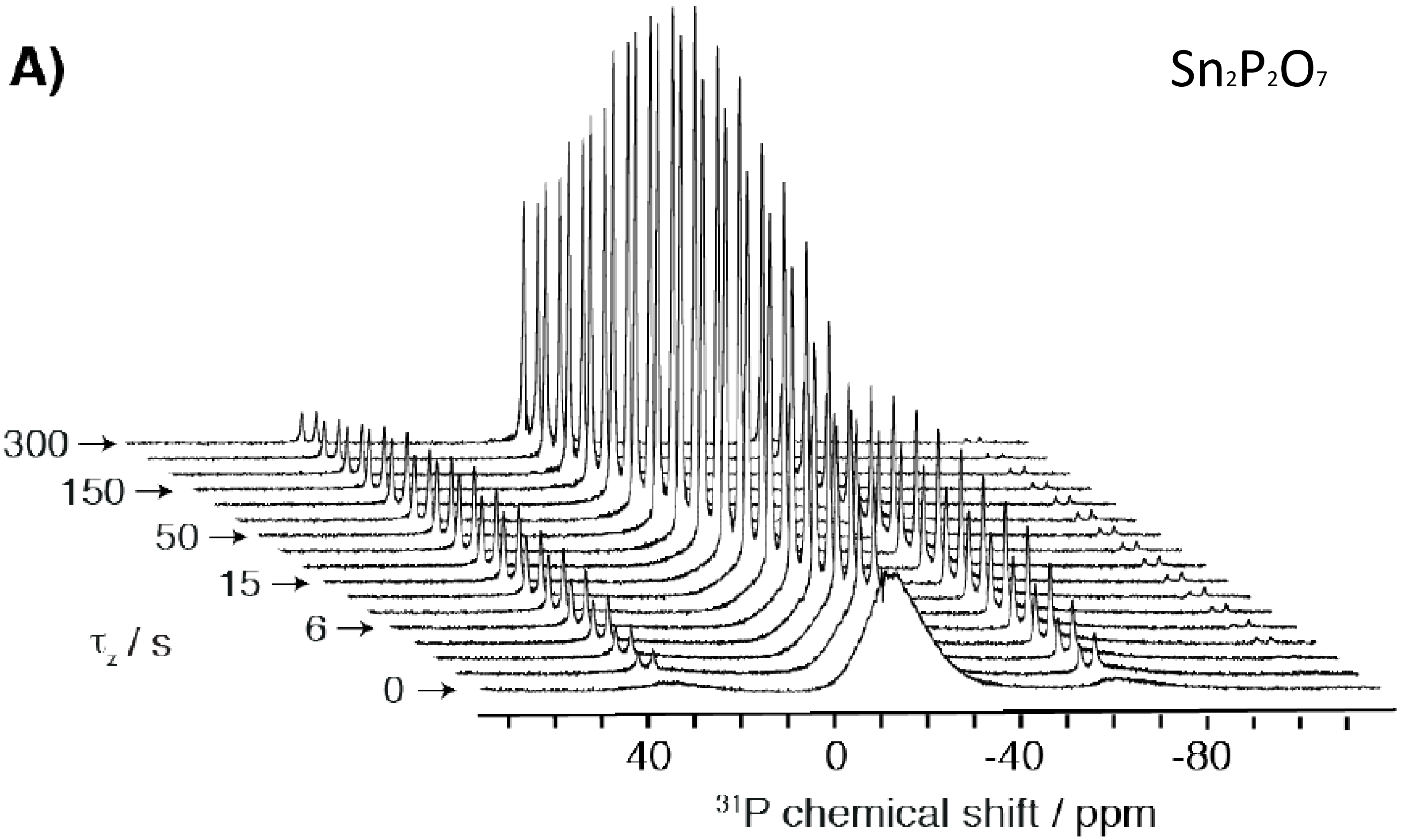


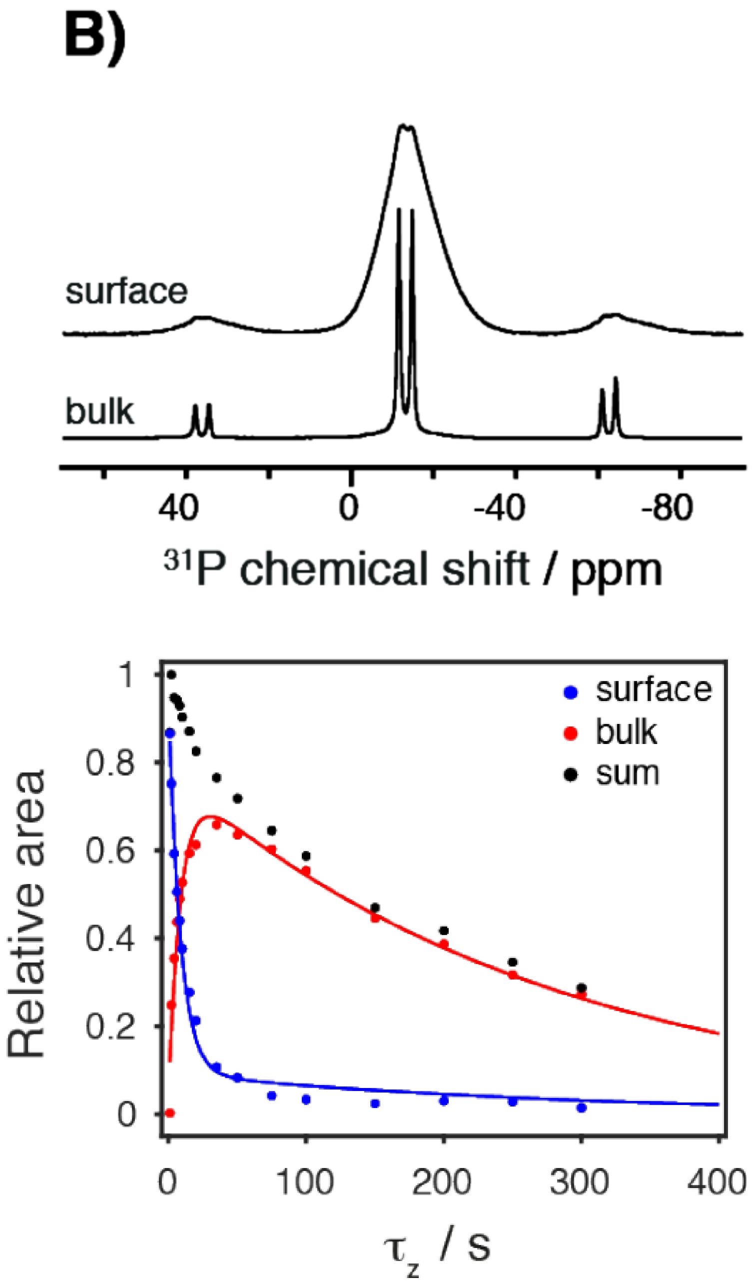
Indirect DNP + Multi-CP



Snædís Björgvinsdóttir, Hyperpolarisation of Inorganic Solids

Relayed DNP





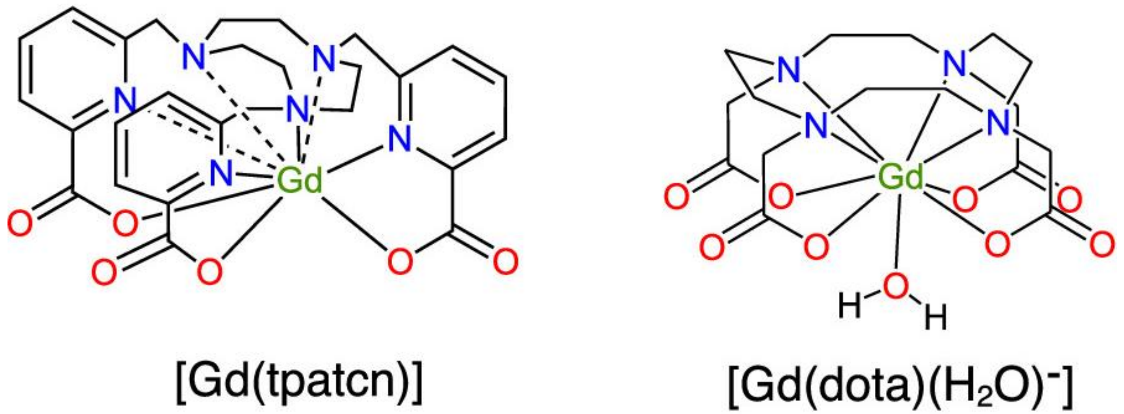
Björgvinsdóttir et al., *J. Magn. Reson.*, 2021

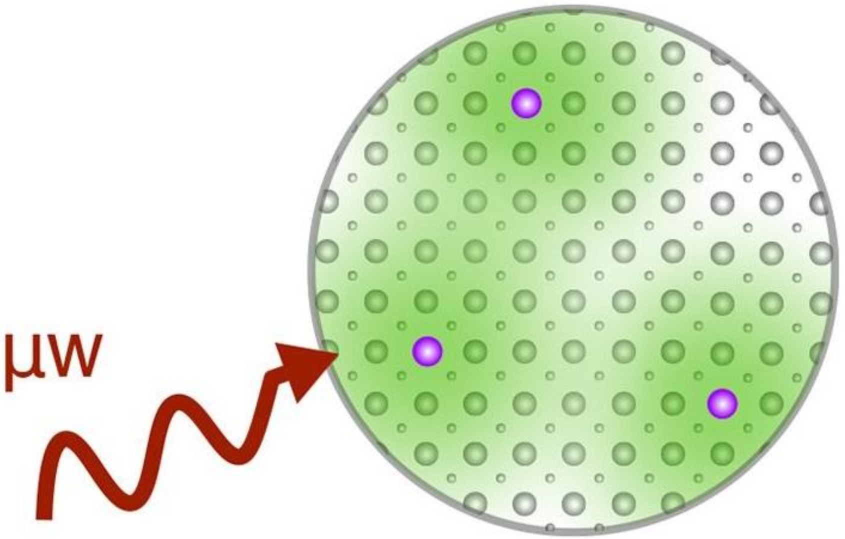
Metal-ion DNP

- Most paramagnetic metals relax too quickly for efficient DNP
- **Except** high-spin ions with no orbital angular momentum
- Mn^{2+} (S = 5/2), Gd^{3+} (S = 7/2), octahedral Cr^{3+} (S = 3/2)
- Primarily solid effect
- $S > 1/2$, subject to zero-field splitting (ZFS)
- Analogous to nuclear quadrupolar coupling. High-symmetry environment needed for narrow lines and efficient DNP

Corzilius, *eMagRes,* 2018

Metal-ion DNP





"Exogenous" DNP

- High-symmetry Gd complexes for frozen-solution / impregnation DNP
- More stable to reduction, e.g. in cell

"Endogenous" DNP

- Metal-ion doped into material
- Inherent bulk sensitivity
- Symmetric sites can give large ε

Stevanato et al., *JACS,* 2019

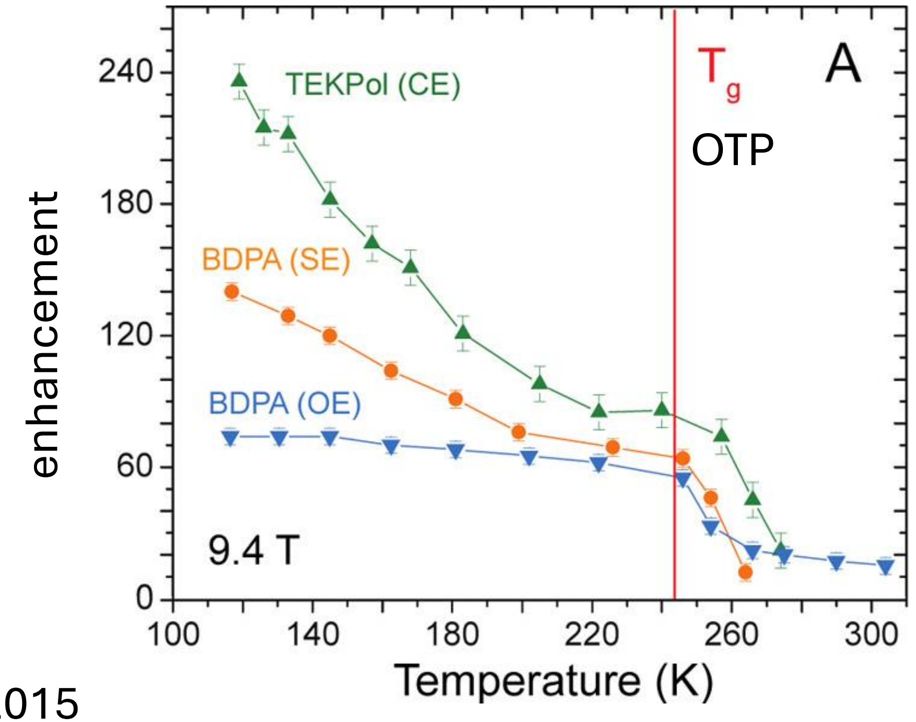
Jardon-Alvarez and Leskes, *Prog. Nucl. Magn. Reson. Spec.* 2023

Summary of DNP Flavours

- Impregnation / exogenous DNP
  - Indirect DNP, $^1H \rightarrow X$
    - ^1H in sample, $^1H \rightarrow X$ CP : **bulk**
    - No ^1H in sample
      - $^1H \rightarrow X$ CP : **surface**
      - $^1H \rightarrow X$ multi-CP : **bulk**
  - Direct DNP of X nuclei
    - Short recycle delay : **surface**
    - Long recycle delay (assuming T_1 is long enough!) : **bulk**
- Endogenous DNP : **bulk**

Temperature

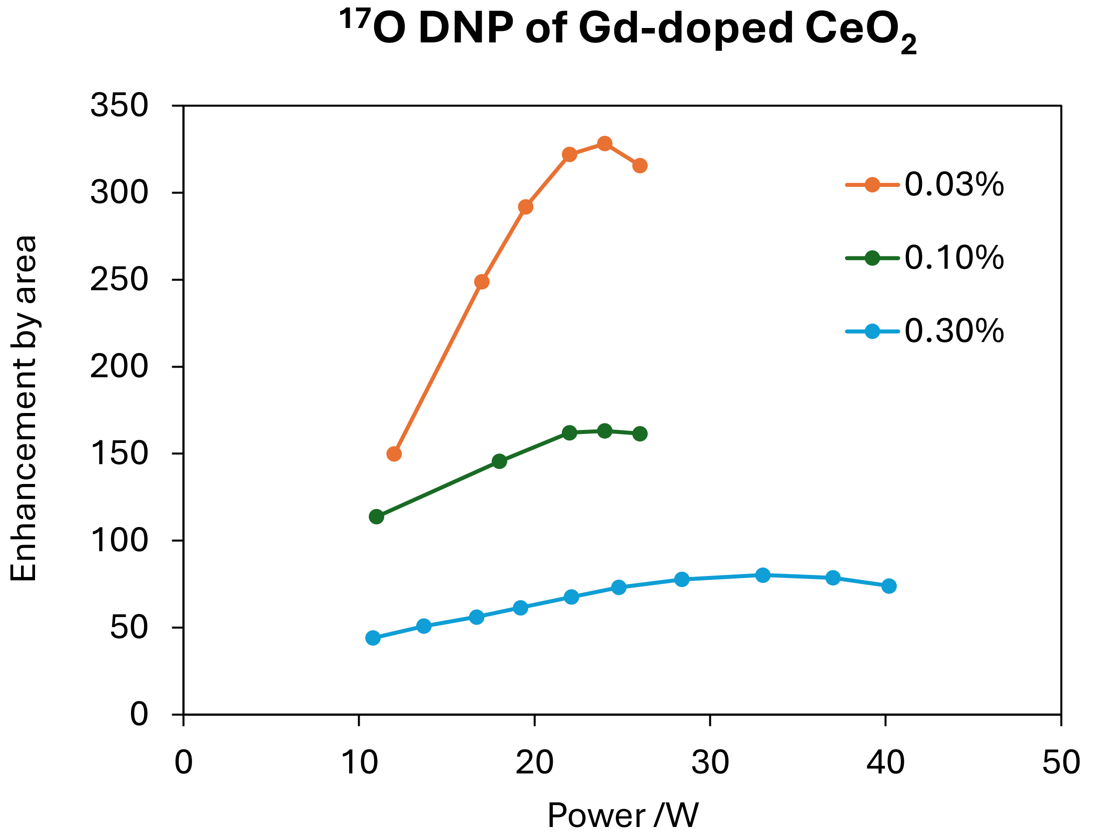
- Commercial MAS DNP systems use LN2: ~100 K
- Helium spinning has also been demonstrated: 30 – 40 K
- Low T slows down the electron relaxation, so it's easier to saturate the transitions
- T dependence also determined by rigidity of glass (and T_g)
- Overhauser effect often run at room temp: e.g., liquids, or Li metal (T_{1e} temp independent)



Lelli et al., *JACS*, 2015

Microwave Power

- Balance greater microwave field with higher sample temp to maximise saturation



Hope et al., *J. Phys. Chem. C*, 2021

With thanks to…

- Warwick NMR group
- Moreno Lelli
- Lyndon Emsley & LRM group
- Federico De Biasi
- Pinelopi Moutzouri
- Pierrick Berruyer

Progress in Nuclear Magnetic Resonance Spectroscopy

Dynamic nuclear polarization for sensitivity enhancement in modern solid-state NMR

Aany Sofia Lilly Thankamony [1], Johannes J. Wittmann [1], Monu Kaushik, Björn Corzilius [*]

Appendix:
Sensitivity in NMR

Sensitivity in NMR

T_2^*: inverse of the linewidth

M_m: nuclear magnetisation (molar)

t_exp: experimental time

c: concentration

$$\mathrm{SNR} \approx M_\mathrm{m}\, c\, \eta\, T_2^* \sqrt{\frac{t_\mathrm{exp}\omega_0 V_\mathrm{C} \mu_0 Q \Delta f}{T_1 4F k_\mathrm{B} T_\mathrm{C}}}$$

T_1 relaxation constant

ω_0: Larmor frequency

T_C: temperature of the coil

η: volume filling-factor in the coil

V_C: volume of coil

Q = Q factor of coil. F: noise factor. Δf = receiver bandwidth

Lepucki et al., The normalized limit of detection in NMR spectroscopy, *J. Magn. Reson.* 2021

How to increase sensitivity?

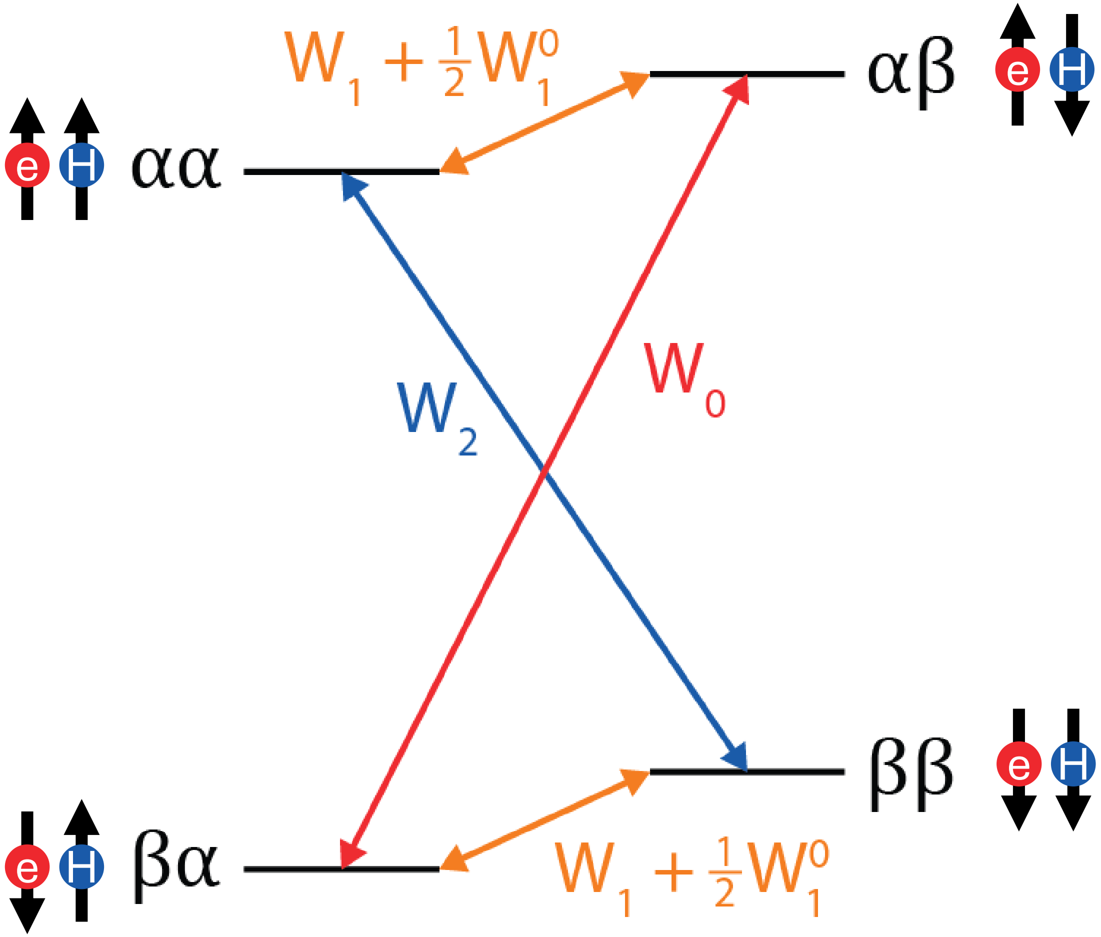
- Increase concentration
- Increase T_2^* (e.g. MAS, decoupling)
- Go to higher field ($\mathrm{SNR} \propto B_0^{3/2}$)
- Make your coil and sample bigger
- Use a cryoprobe
- Reduce T_1 (e.g. PRE)
- Run for longer!

- **Increase Magnetisation**

$$\mathrm{SNR} \approx M_\mathrm{m}\, c\, \eta\, T_2^* \sqrt{\frac{t_\mathrm{exp}\,\omega_0 V_\mathrm{C} \mu_0 Q \Delta f}{T_1 4F k_\mathrm{B} T_\mathrm{C}}}$$

Appendix:
Overhauser effect relaxation rates

Overhauser Effect: Rate Equations



- W_i = 1st order relaxation rate coefficient for each transition
- W_1 = nuclear relaxation induced by e–n coupling
- W_1^0 = nuclear relaxation by any other source = $1/T_1^{\text{pure}}$

$$\frac{d\langle I_z\rangle}{dt} = -(W_0 + 2W_1 + W_2 + W_1^0)(\langle I_z\rangle - I_0) - (W_2 - W_0)(\langle S_z\rangle - S_0)$$

Hausser, Dynamic Nuclear Polarization in liquids, 1968. Bennati and Orlando, eMagRes, 2019
Maly et al., J. Chem. Phys., 2008. Thankamony et al., Prog. Nucl. Magn. Reson. Spectrosc., 2017

Overhauser Effect: Rate Equations

$$\frac{d\langle I_z\rangle}{\mathrm{dt}} = -(W_0 + 2W_1 + W_2 + W_1^0)(\langle I_z\rangle - I_0) - (W_2 - W_0)(\langle S_z\rangle - S_0) = 0$$

$$(\langle I_z\rangle - I_0) = \frac{W_2 - W_0}{W_0 + 2W_1 + W_2 + W_1^0}(S_0 - \langle S_z\rangle)$$

$$\frac{\langle I_z\rangle - I_0}{I_0} = \frac{W_2 - W_0}{W_0 + 2W_1 + W_2 + W_1^0}\frac{S_0 - \langle S_z\rangle}{S_0}\frac{S_0}{I_0}$$

Enhancement: $$\varepsilon = \frac{\langle I_z\rangle}{I_0} = 1 + \frac{W_2 - W_0}{W_0 + 2W_1 + W_2}\frac{W_0 + 2W_1 + W_2}{W_0 + 2W_1 + W_2 + W_1^0}\frac{S_0 - \langle S_z\rangle}{S_0}\frac{\gamma_S}{\gamma_I}$$

Overhauser Effect: Rate Equations

$$\varepsilon = \frac{\langle I_z \rangle}{I_0} = 1 + \frac{W_2 - W_0}{W_0 + 2W_1 + W_2} \frac{W_0 + 2W_1 + W_2}{W_0 + 2W_1 + W_2 + W_1^0} \frac{S_0 - \langle S_z \rangle}{S_0} \frac{\gamma_S}{\gamma_I}$$

$$\varepsilon = 1 - \xi f s \frac{|\gamma_S|}{\gamma_I}$$

Coupling factor: $\xi = \frac{W_2 - W_0}{W_0 + 2W_1 + W_2} = \frac{\sigma_{IS}}{\rho_I}$

Leakage factor: $f = \frac{W_0 + 2W_1 + W_2}{W_0 + 2W_1 + W_2 + W_1^0} = \frac{\rho_I}{\rho_I + W_1^0}$

Saturation factor: $s = \frac{S_0 - \langle S_z \rangle}{S_0}$

$$\frac{d}{dt}\begin{pmatrix} \langle I_z \rangle \\ \langle S_z \rangle \end{pmatrix} = -\begin{pmatrix} \rho_I & \sigma_{IS} \\ \sigma_{IS} & \rho_S \end{pmatrix} \begin{pmatrix} \langle I_z \rangle - I_0 \\ \langle S_z \rangle - S_0 \end{pmatrix}$$

ρ = auto-relaxation rate $\quad$ σ = cross-relaxation rate

Leakage factor

$$\varepsilon = 1 - \xi f s \frac{|\gamma_S|}{\gamma_I}$$

- $f = \frac{W_0 + 2W_1 + W_2}{W_0 + 2W_1 + W_2 + W_1^0} = \frac{\rho_I}{\rho_I + W_1^0}, \quad 0 < f < 1$
- Defines proportion of nuclear relaxation caused by the paramagnetic electron
- Typically close to 1, unless low concentration of radical (small ρ_I), or another very efficient source of relaxation (large W^0)

Saturation factor

$$\varepsilon = 1 - \xi f s \frac{|\gamma_S|}{\gamma_I}$$

- $s = \frac{S_0 - \langle S_z \rangle}{S_0}, \quad 0 < s < 1$
- No saturation, $\langle S_z \rangle = S_0, s = 0$
- Full saturation, $\langle S_z \rangle = 0, s = 1$
- The greater the saturation, the larger the enhancement
- $s = 1 - \frac{1+\Omega^2 T_{2e}^2}{1+\Omega^2 T_{2e}^2 + \omega_{1e}^2 T_{1e} T_{2e}}, \qquad \Omega = \omega_{\mu w} - \omega_{0S}$ (electron offset)

  ω_{1e} = microwave power
- SQ transition is allowed, so less μw power required to saturate

Coupling factor

$$\varepsilon = 1 - \xi f s \frac{|\gamma_S|}{\gamma_I}$$

- $\xi = \frac{W_2 - W_0}{W_0 + 2W_1 + W_2} = \frac{\sigma_{IS}}{\rho_I}$, $\quad -1 < \xi < \frac{1}{2}$
- Measures if ZQ or DQ relaxation dominates
- $W_2 > W_0$, $\xi > 1$, negative enhancement
- $W_2 < W_0$, $\xi < 1$, positive enhancement
- Same sign rules as solid effect – but we can't choose ZQ or DQ

For positive γ_I !

What determines the relaxation rates?

Solomon Theory

- Hyperfine coupling Hamiltonian: $\hat{H} = \hat{\boldsymbol{S}} \cdot \mathbb{A} \cdot \hat{\boldsymbol{I}}$
- Hyperfine coupling can have scalar (Fermi contact) and/or dipolar components: $\mathbb{A} = A^{\mathrm{FC}} + \mathbb{A}^{\mathrm{dip}}$

Solomon Theory – Fermi Contact

- Fermi contact is isotropic:
- $\hat{H} = A^{\text{FC}}\,\hat{\mathbf{I}}\cdot\hat{\mathbf{S}} = A^{\text{FC}}\left[\hat{I}_z\hat{S}_z + \frac{1}{2}\left(\hat{I}_+\hat{S}_- + \hat{I}_-\hat{S}_+\right)\right]$
- This can only induce ZQ relaxation ($\hat{I}_+\hat{S}_-$ and $\hat{I}_-\hat{S}_+$ terms)
- $W_1 = W_2 = 0.$ $\xi = \frac{-W_0}{W_0} = -1.$ Positive enhancement for positive γ_I

$$\varepsilon = 1 - \xi f s \frac{|\gamma_S|}{\gamma_I}$$

Solomon Theory – Dipolar Coupling

- Dipolar coupling is anisotropic, giving SQ ($\hat{I}_+\hat{S}_z, \hat{I}_-\hat{S}_z$) and DQ terms ($\hat{I}_+\hat{S}_+, \hat{I}_-\hat{S}_-$)

- $\xi = \frac{W_2^{\text{dip}} - W_0^{\text{dip}}}{W_0^{\text{dip}} + 2W_1^{\text{dip}} + W_2^{\text{dip}}}$

- Relaxation is driven by the spectral density of the fluctuating interactions at the transition frequency, $J(\omega, \tau)$, where τ is the correlation time of the fluctuations.

$$W_0^{\text{dip}} = k_{\text{dip}}\, J(\omega_S - \omega_I, \tau_{\text{dip}})$$

$$W_1^{\text{dip}} = \frac{3}{2} k_{\text{dip}}\, J(\omega_I, \tau_{\text{dip}})$$

$$W_2^{\text{dip}} = 6\, k_{\text{dip}}\, J(\omega_S + \omega_I, \tau_{\text{dip}})$$

Solomon Theory

- Noting that $\omega_S \gg \omega_I$, $(\omega_S - \omega_I) \approx (\omega_S + \omega_I) \approx \omega_S$
- $\xi = \frac{W_2^{\mathrm{dip}} - W_0^{\mathrm{dip}}}{W_0^{\mathrm{dip}} + 2W_1^{\mathrm{dip}} + W_2^{\mathrm{dip}}} = \frac{5k_{\mathrm{dip}} J(\omega_S, \tau_{\mathrm{dip}})}{7k_{\mathrm{dip}} J(\omega_S, \tau_{\mathrm{dip}}) + 3k_{\mathrm{dip}} J(\omega_I, \tau_{\mathrm{dip}})}$
- Spectral density is Lorentzian: $J(\omega, \tau) = \frac{\tau}{1+\omega^2\tau^2}$

$$W_0^{\mathrm{dip}} = k_{\mathrm{dip}}\, J(\omega_S - \omega_I, \tau_{\mathrm{dip}})$$

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- Spectral density is Lorentzian: $J(\omega, \tau) = \frac{\tau}{1 + \omega^2 \tau^2}$
- $\tau_{\text{dip}} \sim 10 - 100$ ps.
- At all reasonable fields, $\omega_I \tau_{\text{dip}} \ll 1$, $J(\omega_I, \tau_{\text{dip}}) = \tau_{\text{dip}}$
- Below a field of ~0.1 T, $\omega_S \tau_{\text{dip}} \ll 1$, $J(\omega_S, \tau_{\text{dip}}) = \tau_{\text{dip}}$

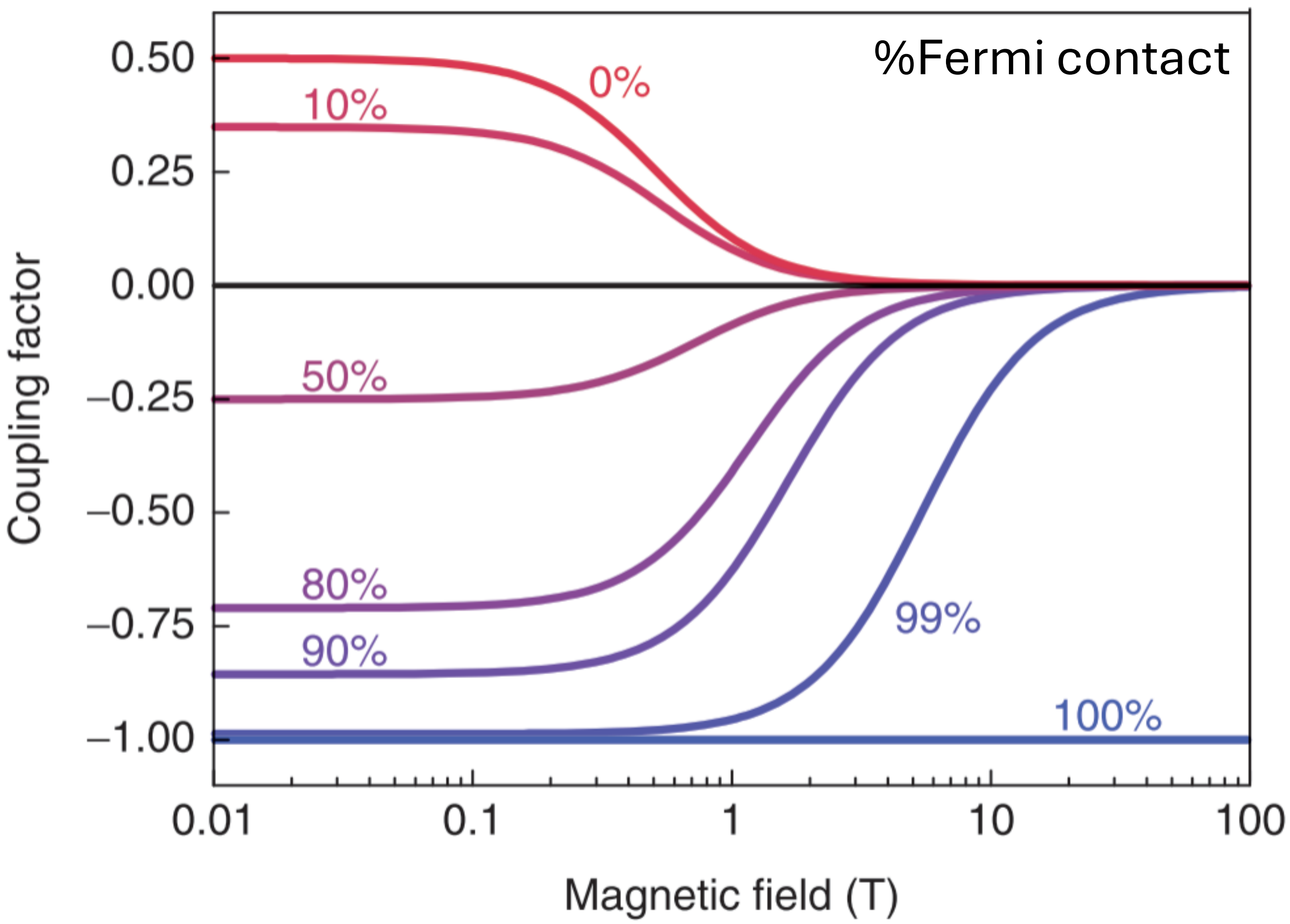
Solomon Theory

$$\varepsilon = 1 - \xi f s \frac{|\gamma_S|}{\gamma_I}$$

$$J(\omega, \tau) = \frac{\tau}{1 + \omega^2 \tau^2}$$

- $\xi = \frac{5k_{\text{dip}} J(\omega_S, \tau_{\text{dip}})}{7k_{\text{dip}} J(\omega_S, \tau_{\text{dip}}) + 3k_{\text{dip}} J(\omega_I, \tau_{\text{dip}})}$
- At low field, $J(\omega_S, \tau_{\text{dip}}) = J(\omega_I, \tau_{\text{dip}}) = \tau_{\text{dip}}$
- $\xi = \frac{5k_{\text{dip}}\tau_{\text{dip}}}{10\, k_{\text{dip}}\tau_{\text{dip}}} = +\frac{1}{2}$, negative enhancement for positive γ_I
- At high field, $\omega_S \tau_{\text{dip}} \gg 1$, $J(\omega_S, \tau_{\text{dip}}) = \frac{1}{\omega_S^2 \tau_{\text{dip}}} \ll J(\omega_I, \tau_{\text{dip}})$
- $J(\omega_I, \tau_{\text{dip}})$ dominates, $\xi \approx \frac{1}{3k_{\text{dip}} J(\omega_I, \tau_{\text{dip}})} \approx 0$

Coupling factor field dependence



Bennati and Orlando, eMagRes, 2019

- Overhauser only works at high field if dominated by Fermi Contact (scalar)
- Any dipolar contribution will dominate at high enough field, suppressing the Overhauser effect.