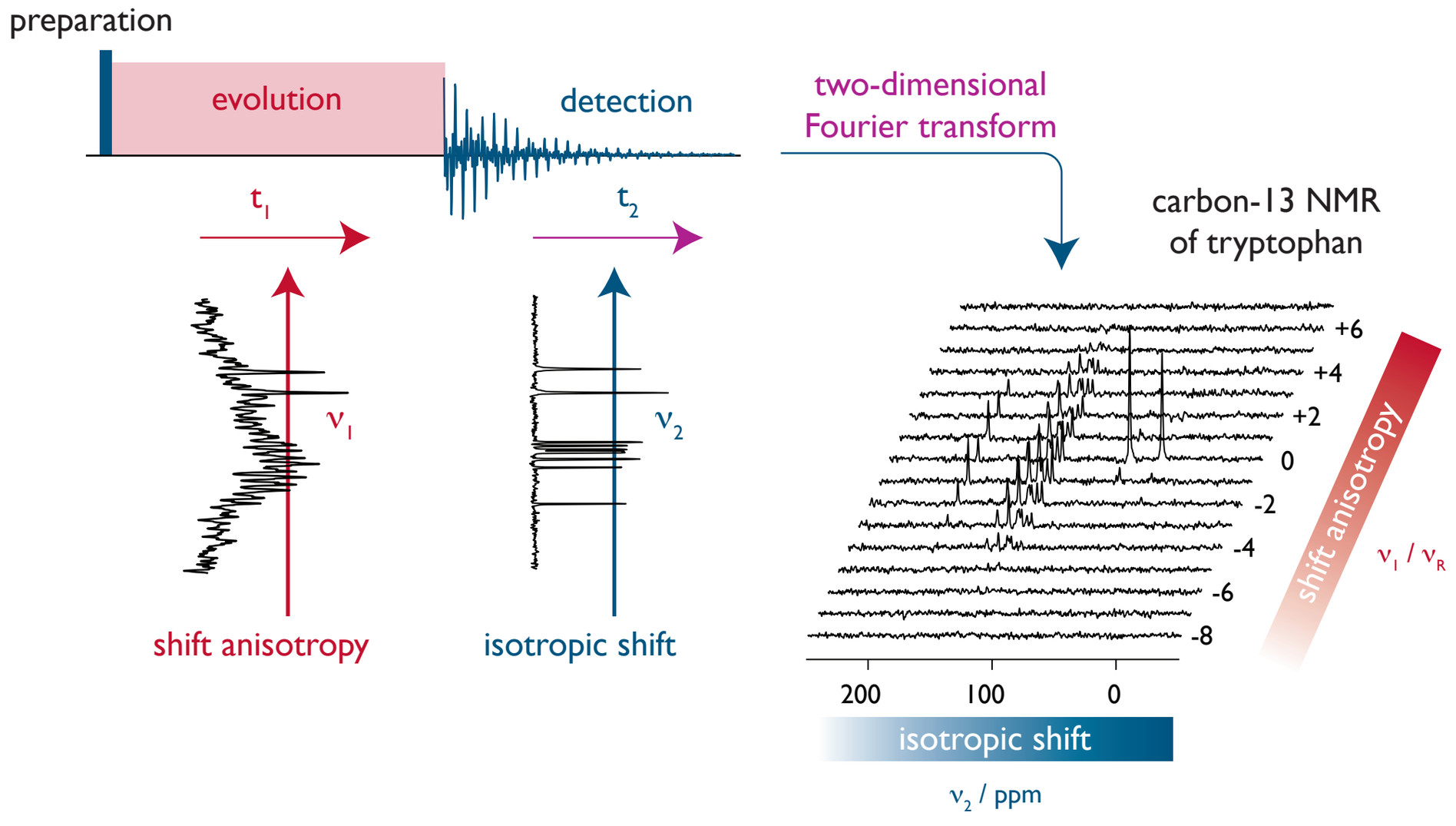
Two-dimensional separation experiments: measuring anisotropic interactions

Jeremy Titman,
School of Chemistry, University of Nottingham

Two-dimensional separation experiments

A two-dimensional separation experiment consists of three time periods: Preparation, evolution and detection.

- The evolution and detection Hamiltonians are different.
- The two-dimensional spectrum separates the spectra which result from the two Hamiltonians.



Philosophy

"Solution-like" approach:
Rapid MAS, Efficient Decoupling
$H = H_{iso}$
No orientational information; recoupling

"Classical solids" approach:
Slow (or no) MAS
H = ?
Retain orientational information

Types of separation

Shift anisotropy and isotropic shift

- Many experiments have been designed which separate the isotropic and anisotropic parts of the chemical shift Hamiltonian.
- These are used to obtain the shift anisotropies of complicated molecules where overlap of powder patterns or sideband manifolds from different chemical sites prevents their measurement using a one-dimensional spectrum.

Heteronuclear dipolar coupling and chemical shift

- The archetypal two-dimensional separation method is the "separated local field" experiment
- This is used to establish the orientation of the principal axis system of the chemical shift tensor relative to the molecule.

Experimental approaches

Wideline separation

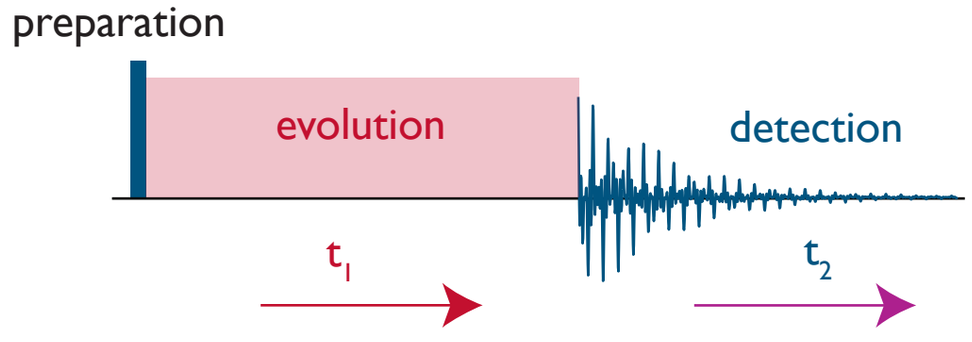
- A non-spinning experiment gives a powder lineshape in two dimensions

Recoupled Hamiltonian

- MAS gives resolution in ν_2 while a recoupling sequence reintroduces the desired Hamiltonian to give a "powder pattern" in ν_1.

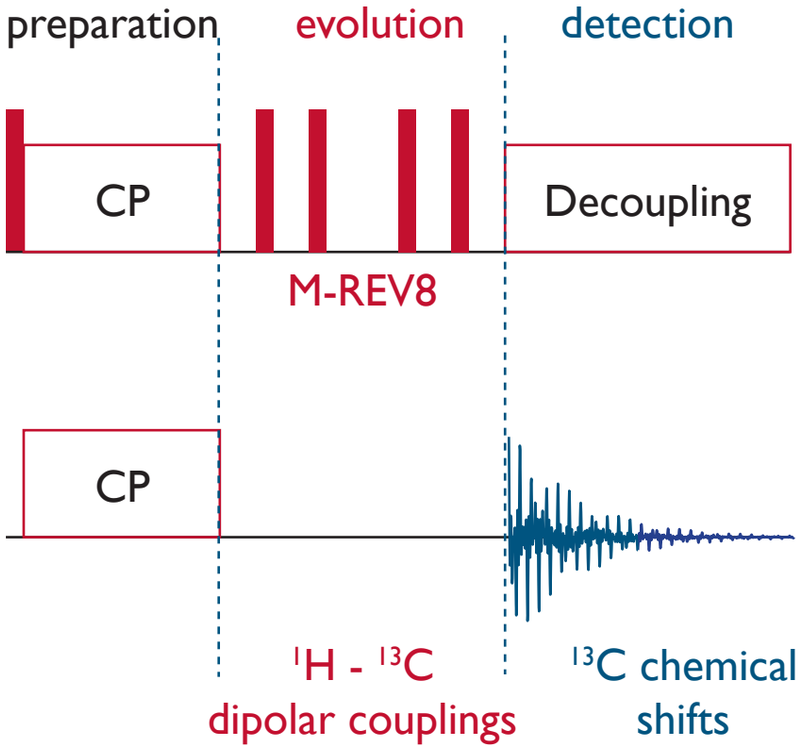
Separation of MAS sideband manifolds

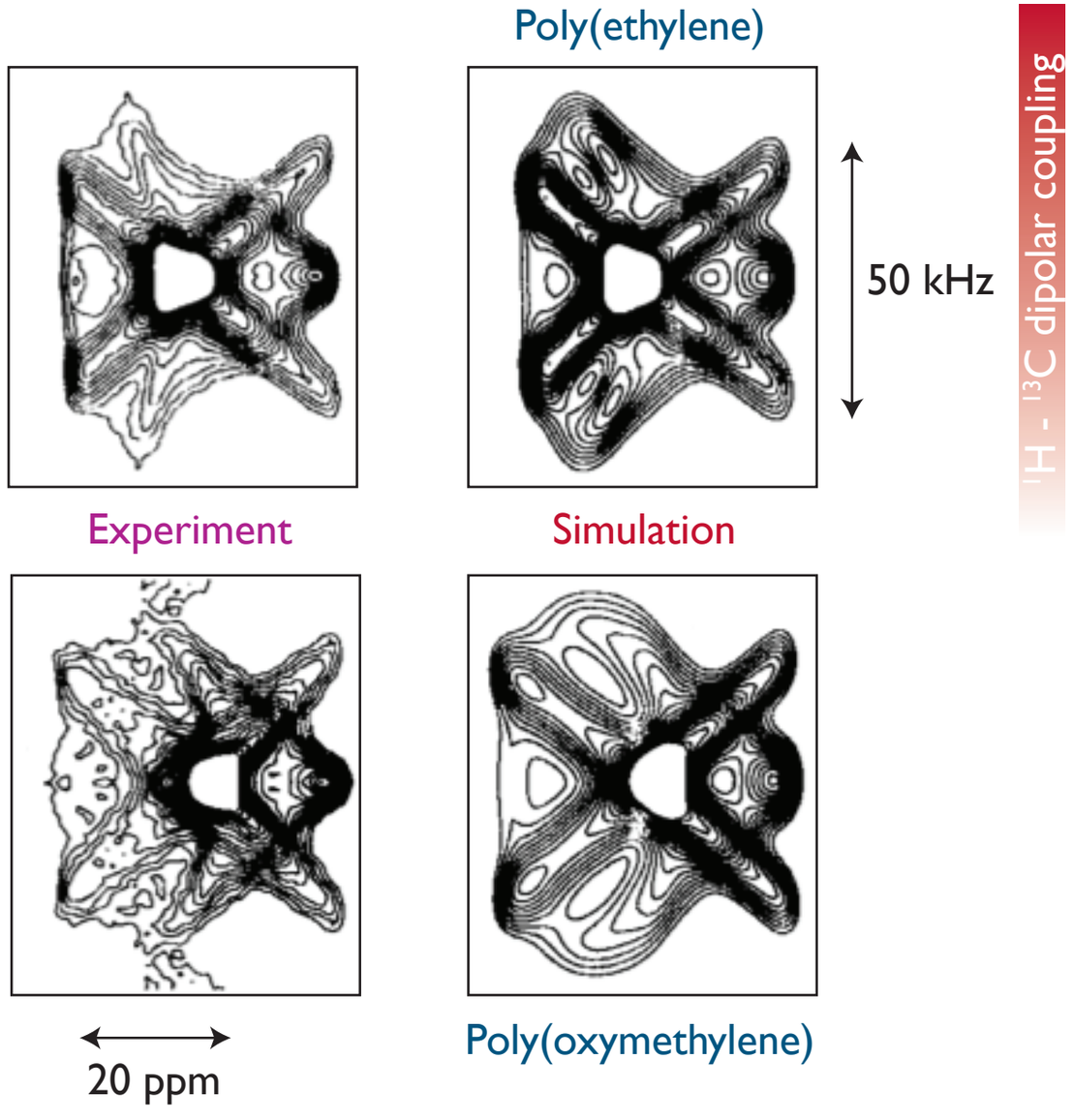
- Sideband manifolds in ν_1 are separated by the isotropic shift in ν_2.
- With very slow spinning ("magic angle turning") sequences of π pulses are used to give the isotropic shift in ν_1 and sideband manifolds in ν_2.



“Separated local field” experiment

- This separates the heteronuclear dipolar coupling in ν_1 and the chemical shift in ν_2.
- The resulting two-dimensional spectrum depends on the relative orientation of the dipolar coupling tensor (with the z axis along the internuclear vector) and the chemical shift tensor (usually with an unknown orientation).





K. Schmidt-Rohr, M. WIlhelm, A, Johansson and H.W. Spiess, *Magn. Reson. Chem.*, **31**, 352 (1993).

Separation of "recoupled" powder patterns

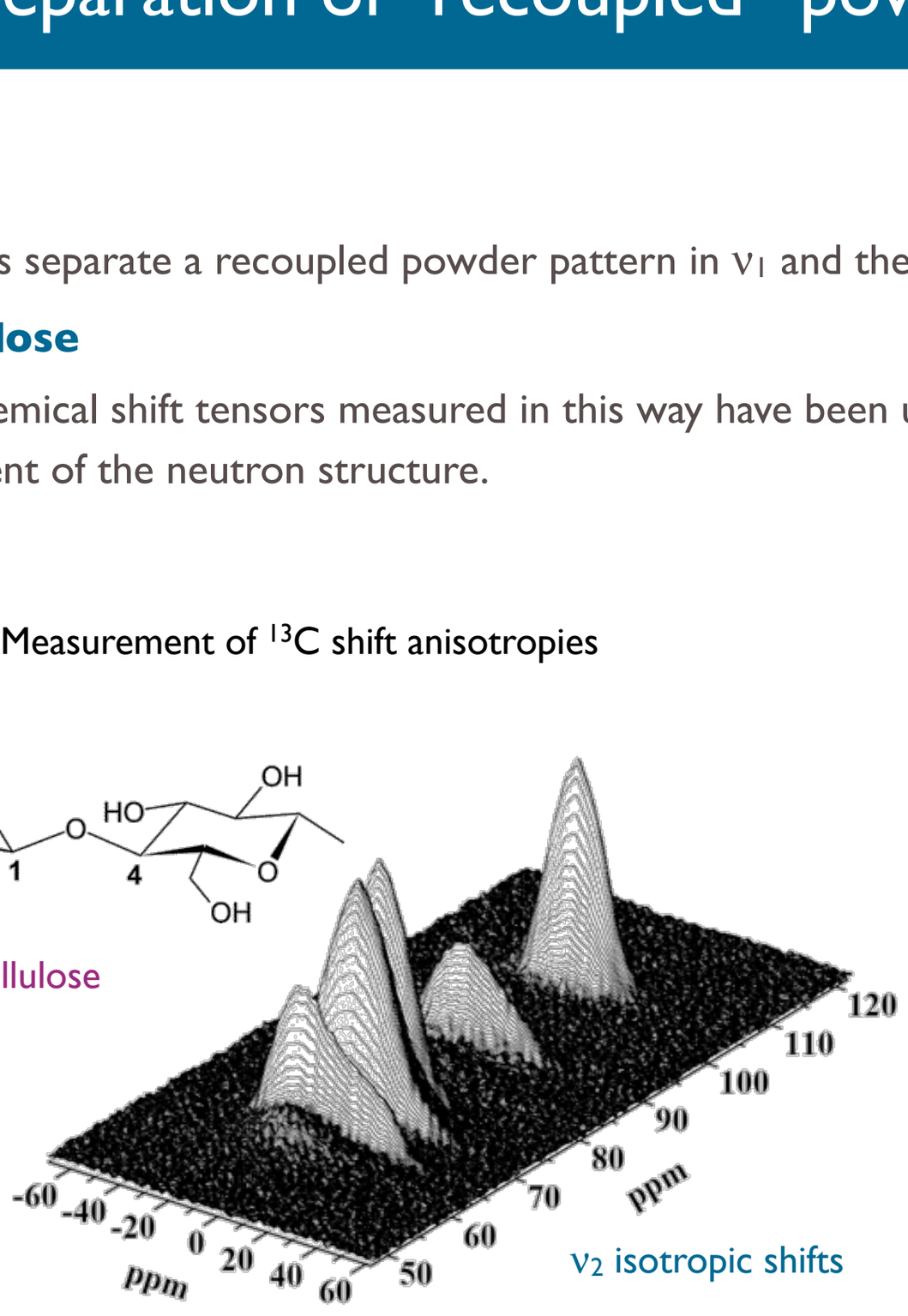
These experiments separate a recoupled powder pattern in ν_1 and the isotropic shift in ν_2.

Example: cellulose

The carbon-13 chemical shift tensors measured in this way have been used as restraints in a molecular dynamics refinement of the neutron structure.

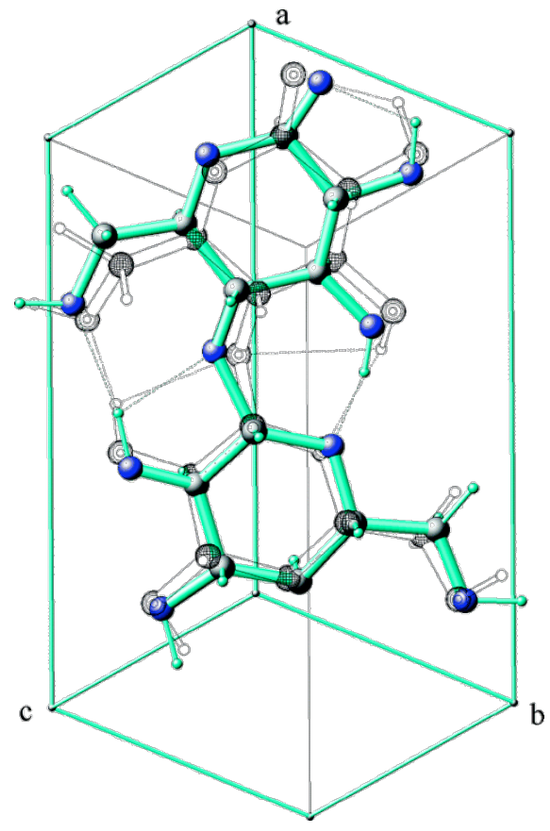
Measurement of ^{13}C shift anisotropies

Cellulose



ν_1 shift anisotropy
via powder pattern

ν_2 isotropic shifts

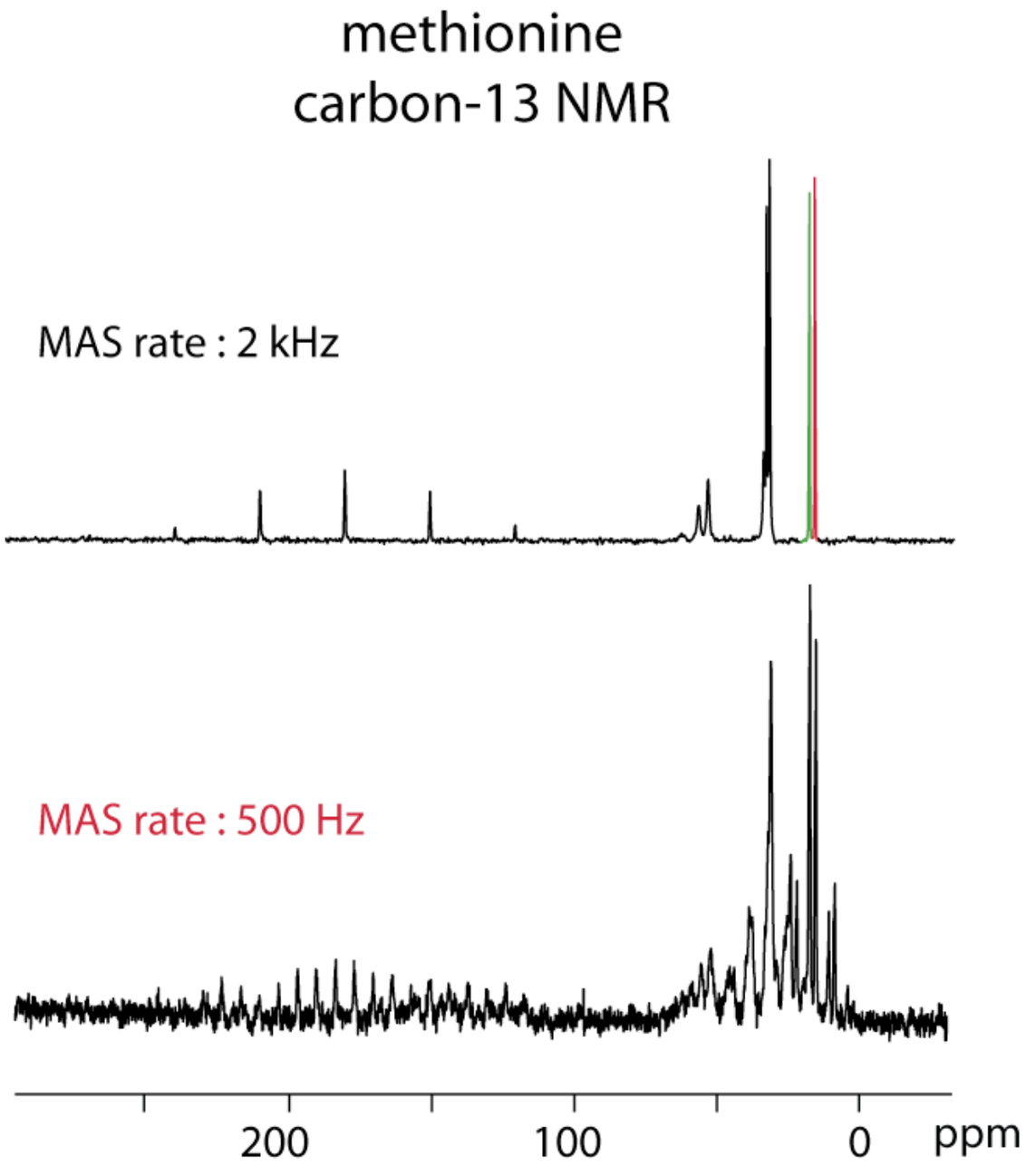


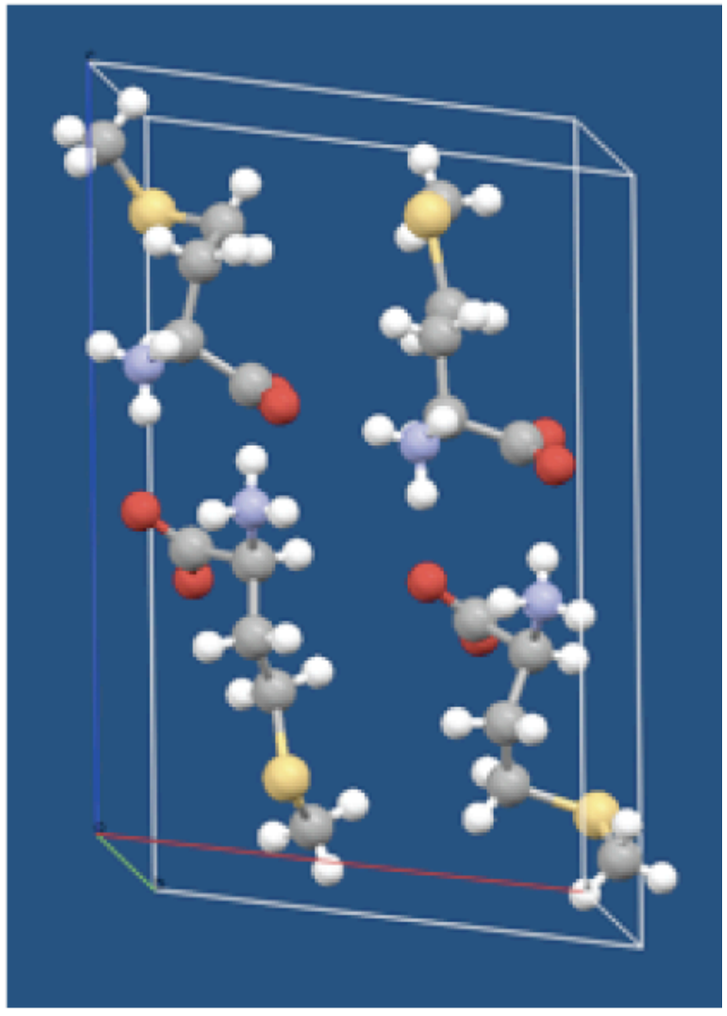
Chemical shift optimized structure
compared with neutron diffraction data

R. Witter, U. Sternberg, S. Hesse, T. Kondo, F. T. Koch and A. S. Ulrich, *Macromolecules*, **39**, 6125 (2006).

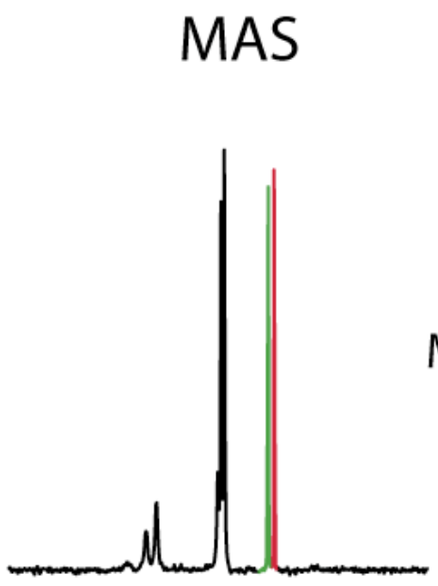
Shift anisotropies by MAS sidebands

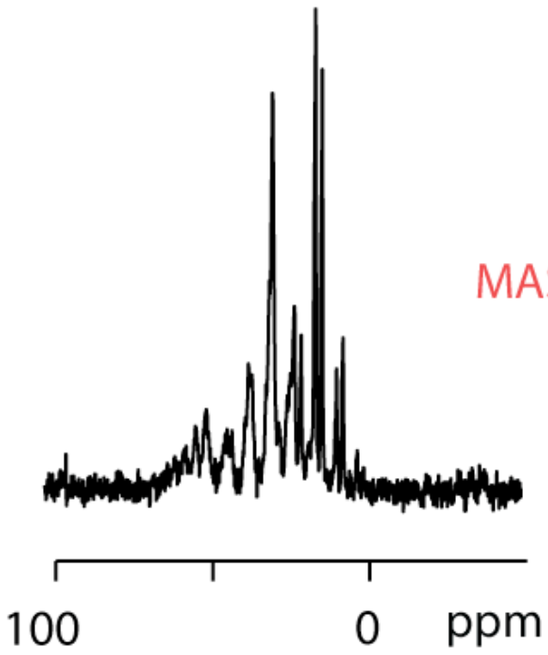
- MAS allows the resolution of different chemical environments via their isotropic shifts.
- With slow MAS the envelope of the sideband intensities reflects the shift anisotropy.
- A few sidebands give a more reliable result for the anisotropy than a wideline spectrum.





Problems with MAS sideband measurements





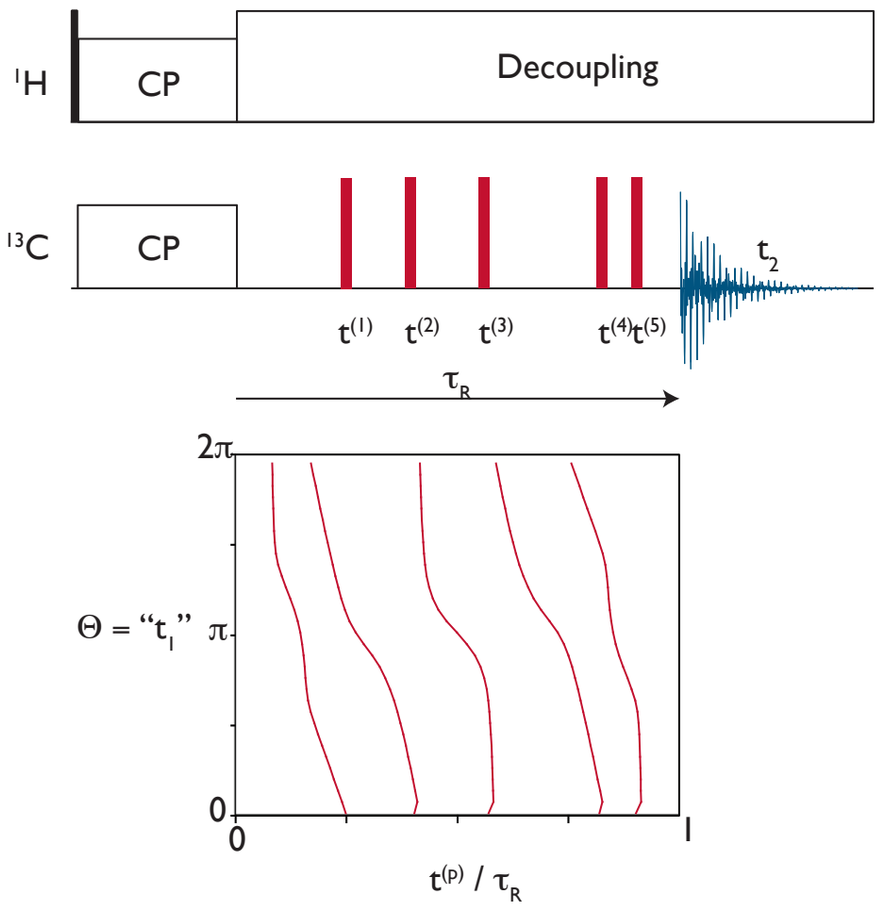
There are many problems when measuring sideband intensities:

- sideband manifolds from different sites overlap
- for small shift tensors even at the slowest stable MAS rates there are not enough sidebands
- modern decoupling methods require fast MAS
- there are sideband pattern distortions due to homonuclear dipolar couplings

2D-PASS

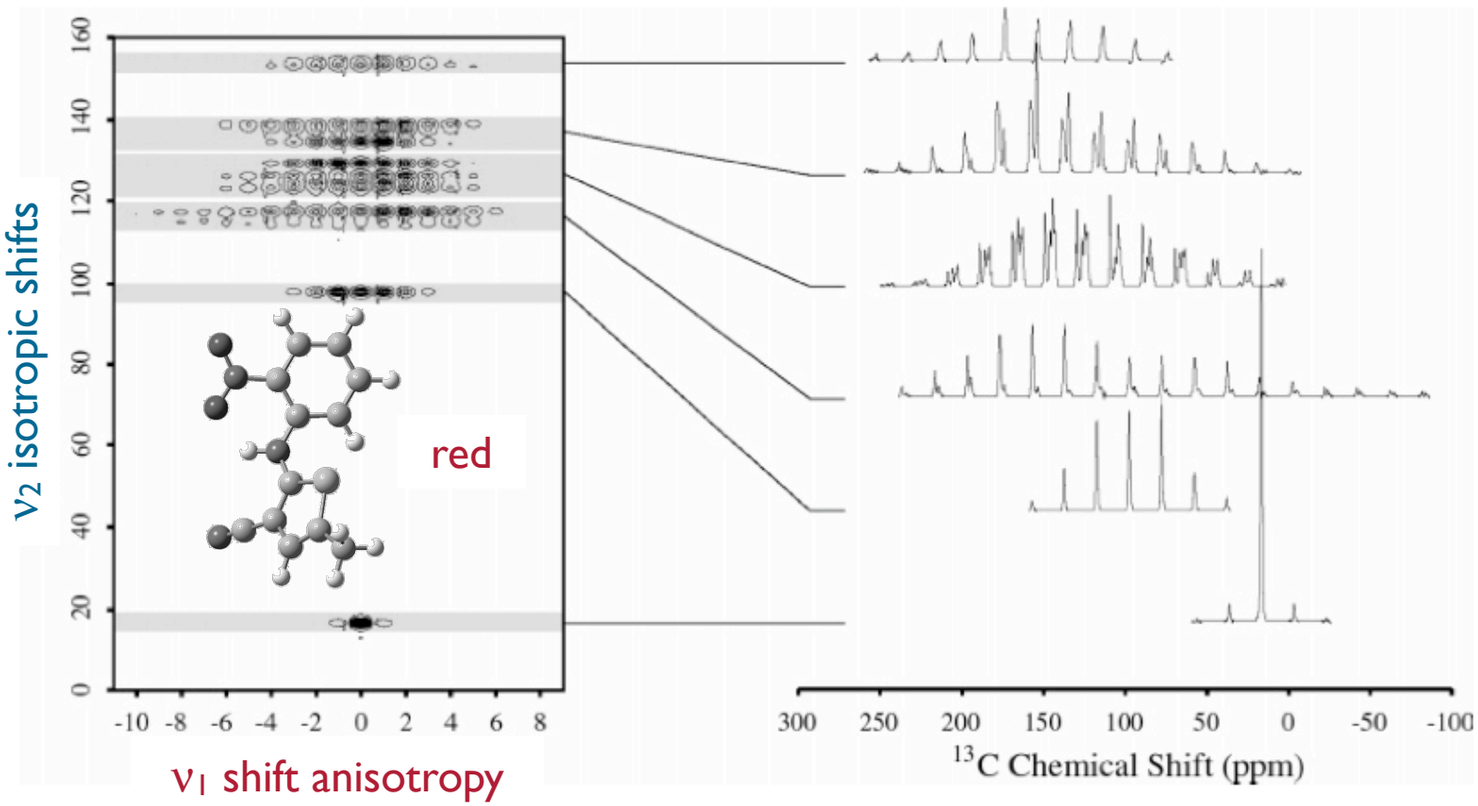
This experiment separates the anisotropic part of the chemical shift measured via the sideband manifold in ν_1 and the isotropic shift in ν_2. Advantages of 2D-PASS include:

- a minimal number of t_1 increments is required
- the ν_1 sideband pattern is identical to the MAS pattern
- the use of short sequences and few π pulses



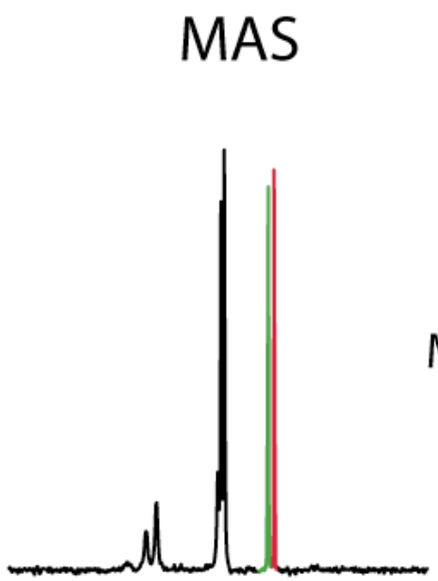
5-methyl-2-[(2-nitrophenyl)amino]

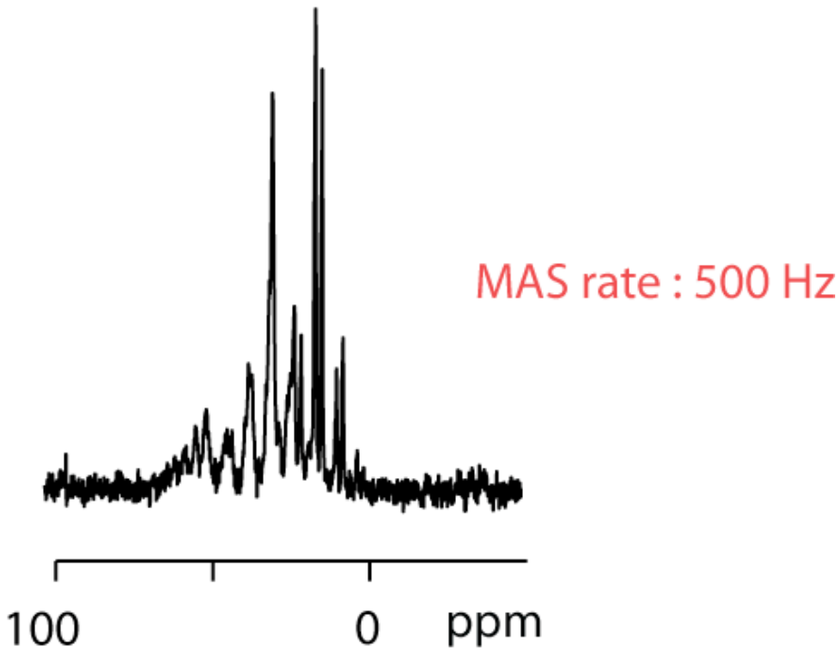
-3-thiophenecarbonitrile



O. N. Antzutkin, S. C. Shekar and M. H. Levitt, *J. Magn. Reson., Ser. A*, **115**, 7 (1995); J. R. Smith. W. Xu and D. Raftery, *J. Phys. Chem. B*, **110**, 7766 (2006).

Problems with MAS sideband measurements





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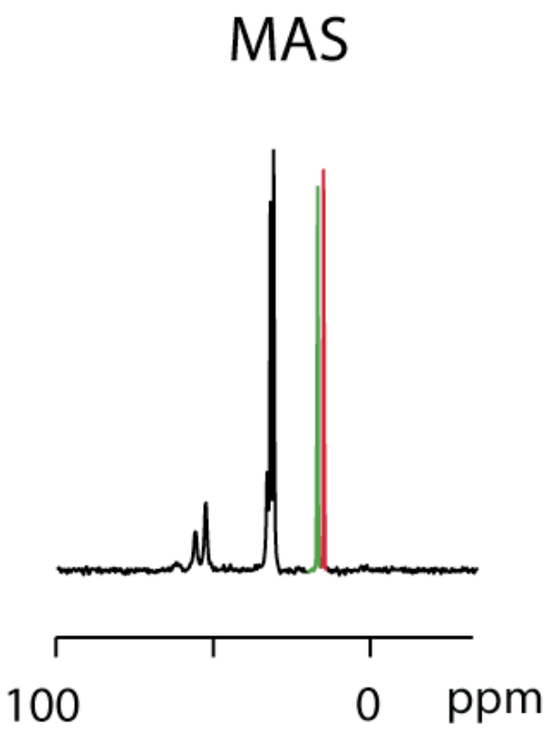
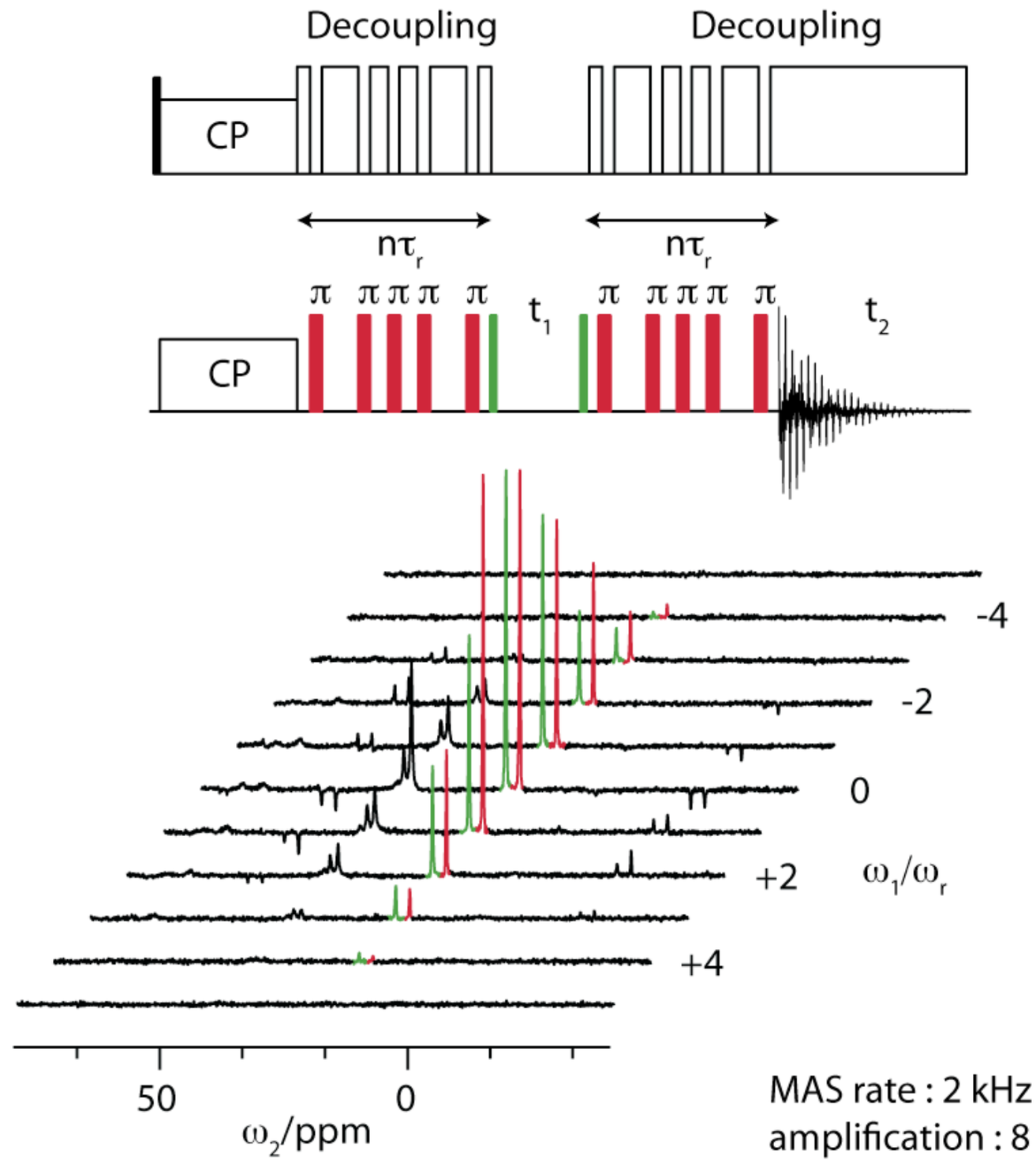
CSA amplification: method



The CSA amplification method separates the fast MAS spectrum in ν_2 from a sideband pattern in ν_1 identical to that observed at some fraction of the actual rate.

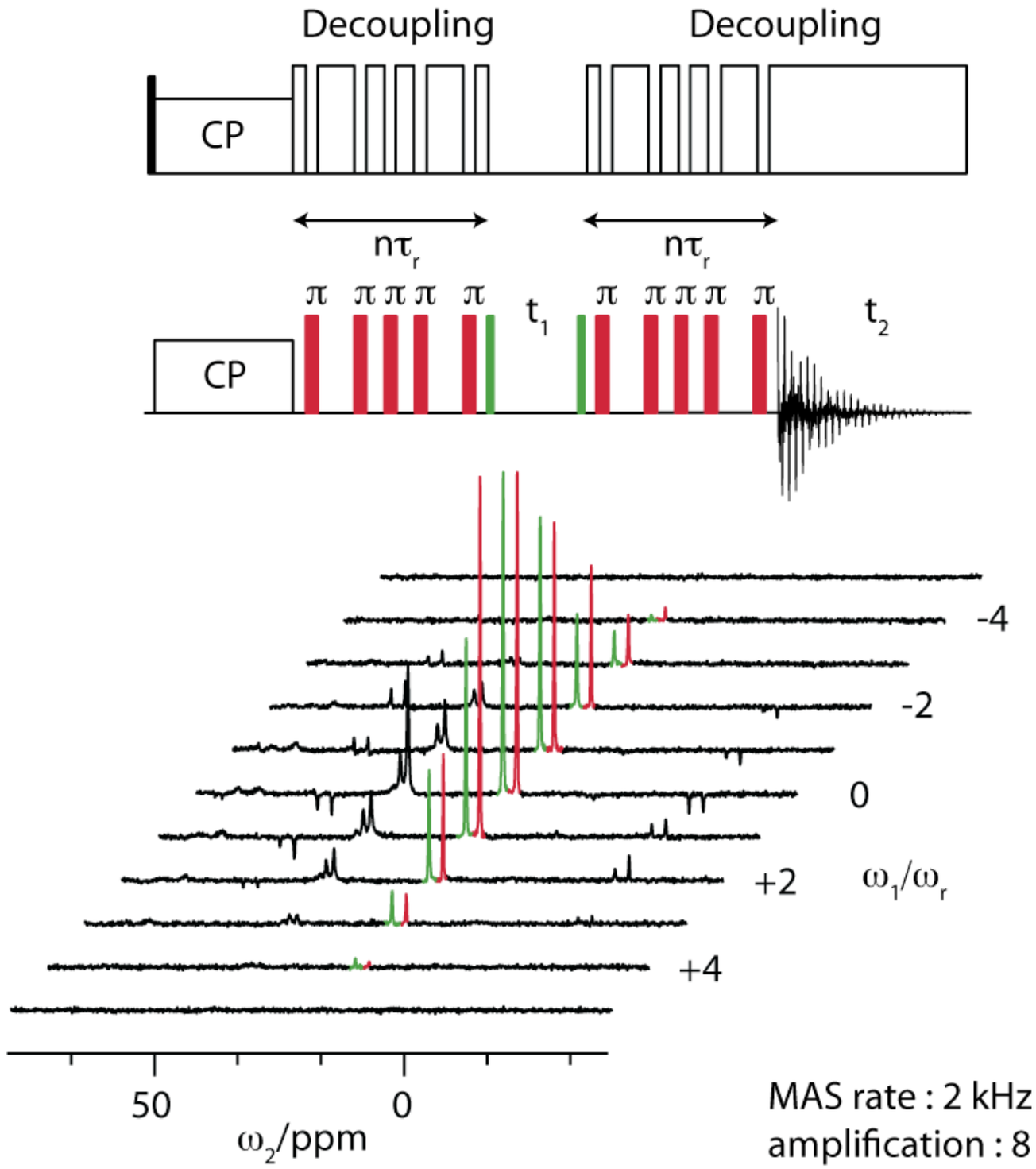


C. Crockford, H. Geen, and J. J. Titman, *Chem. Phys. Lett.*, **344**, 367 (2001); L. Shao, C. Crockford, H. Geen, G. Grasso, and J. J. Titman, *J. Magn. Reson.*, **167**, 75 (2004).

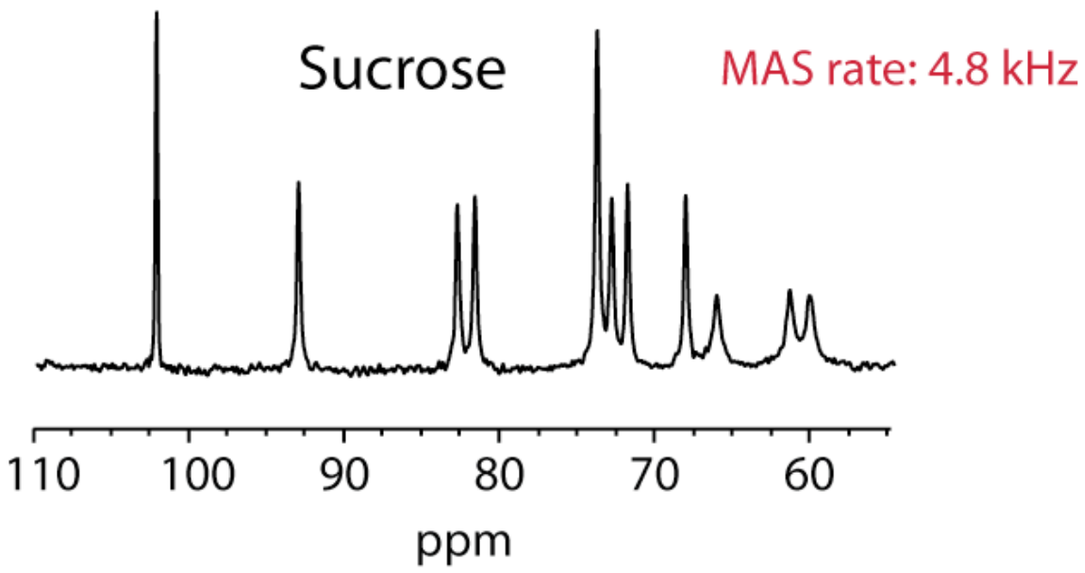
CSA amplification: advantages

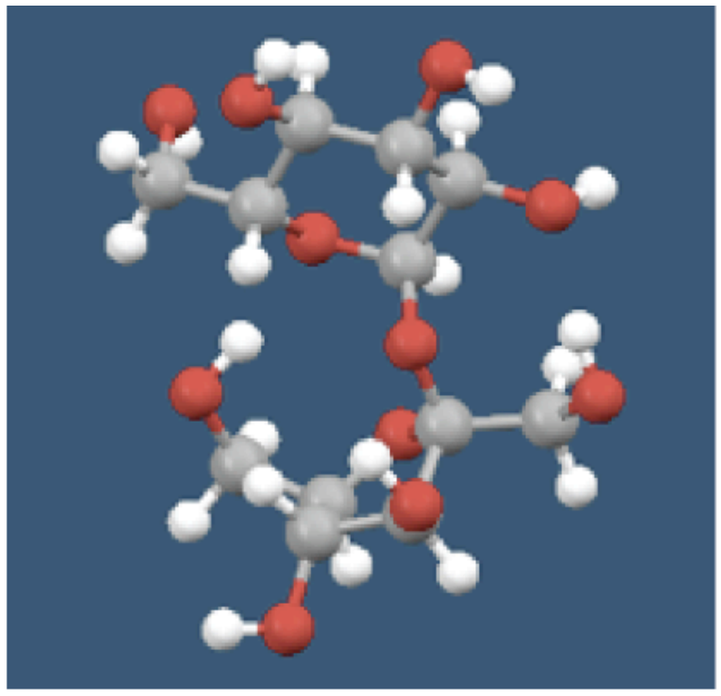
Advantages of the CSA amplification method include:

- a minimal number of t_1 increments is required
- the ν_1 sideband pattern is identical to the slow MAS pattern
- short sequences and few π pulses
- no need for slow unstable spinning even for small shift tensors
- amplification independent of sequence length

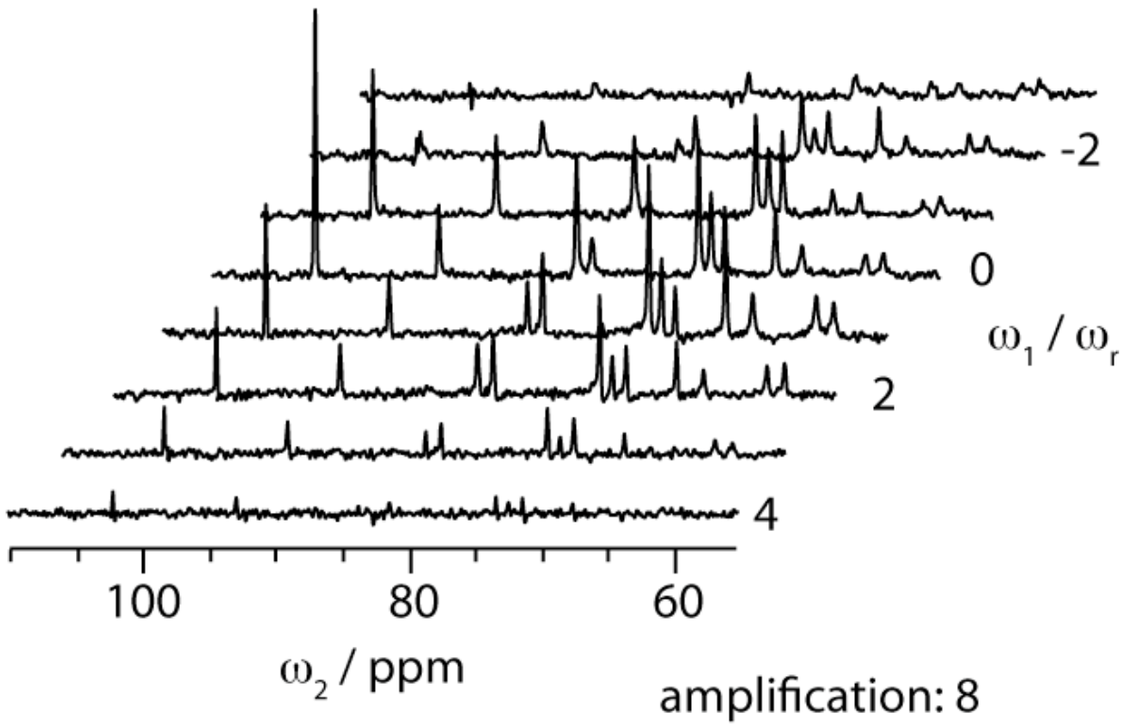


Sucrose

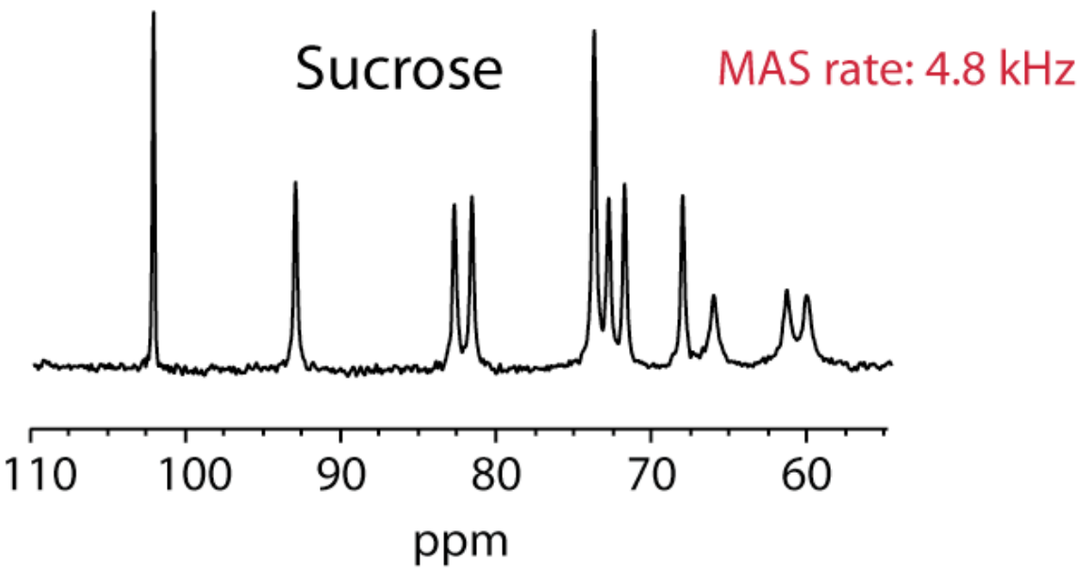


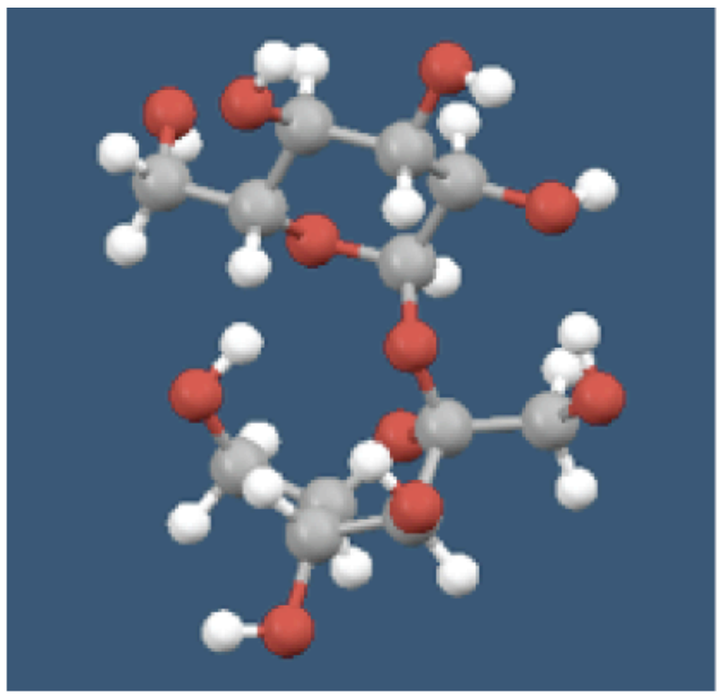


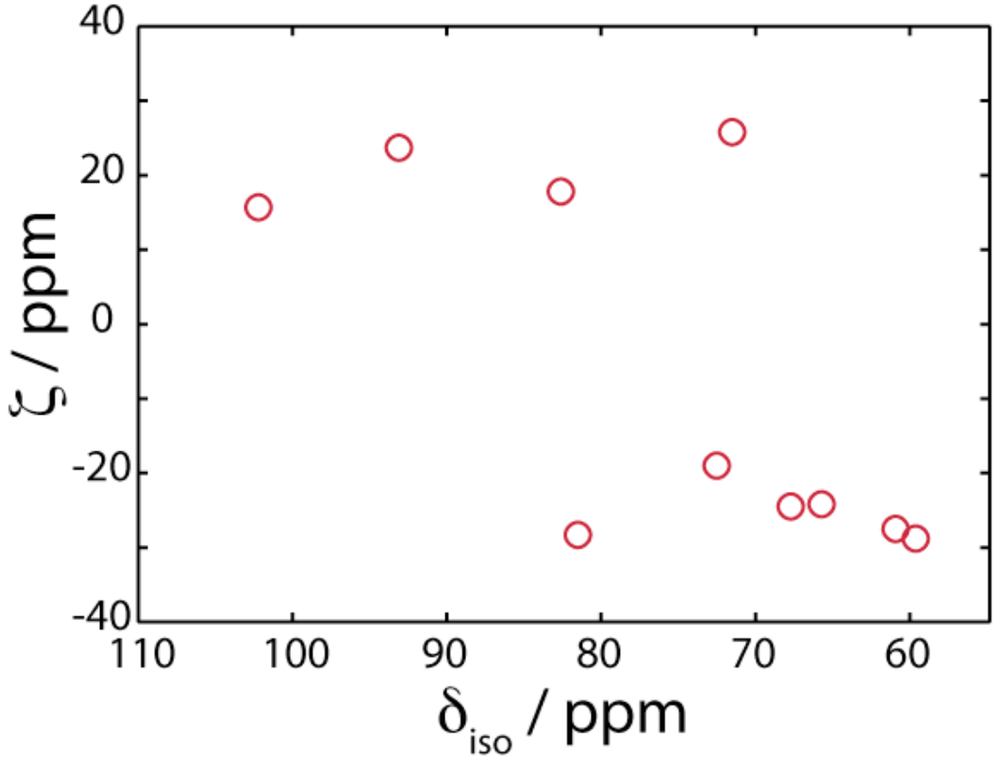
Optimum number of sidebands for measurement of shift anisotropy

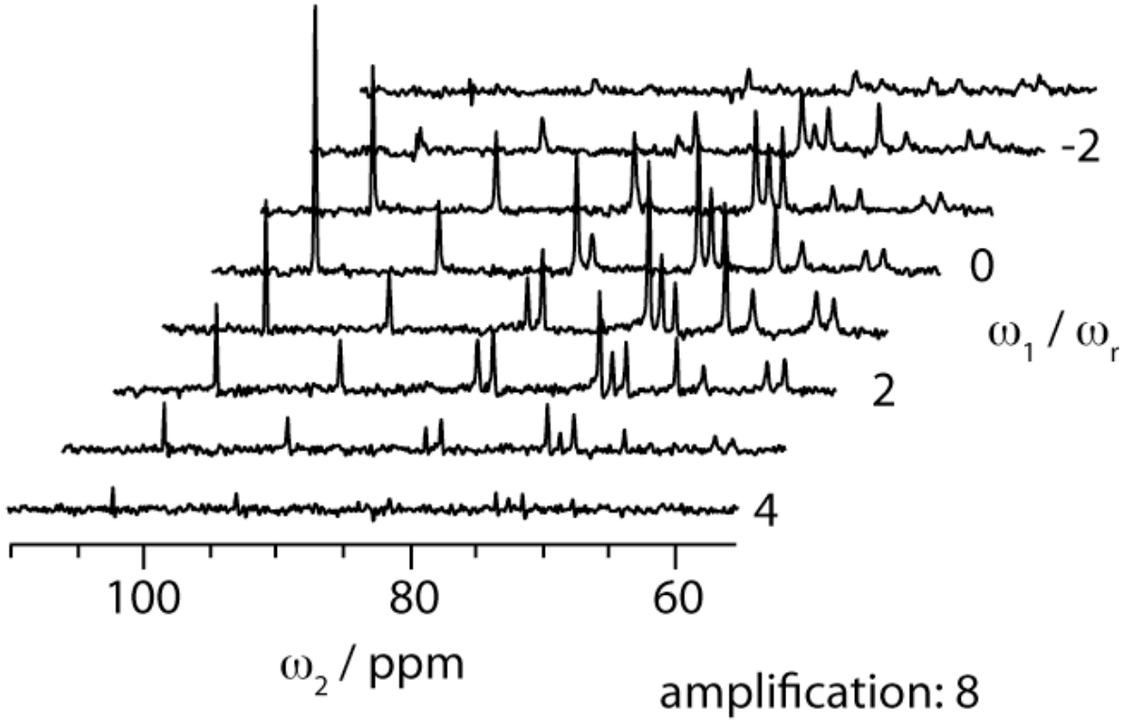


Shift anisotropies by CSA amplification





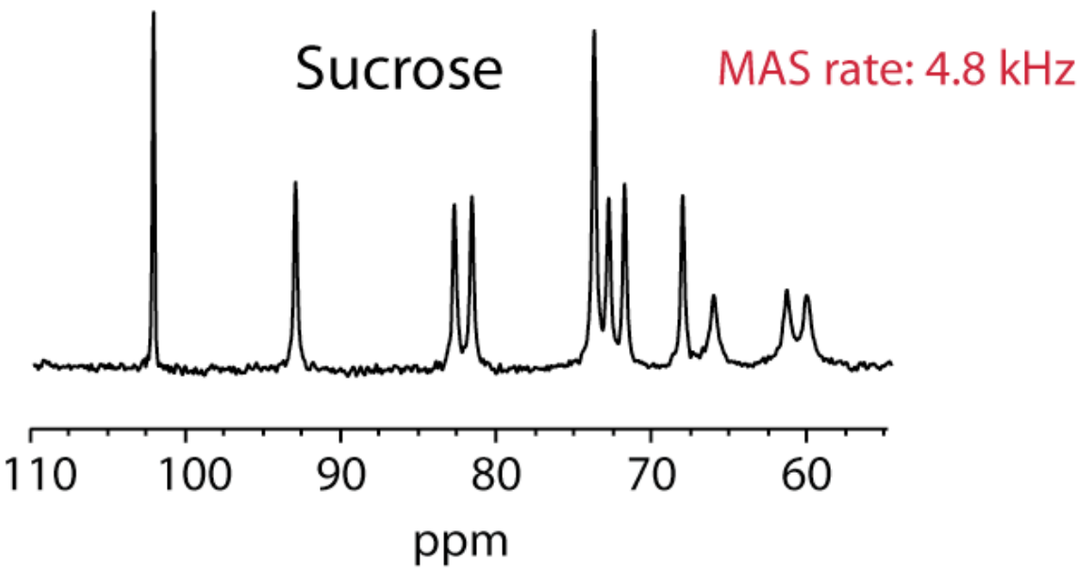


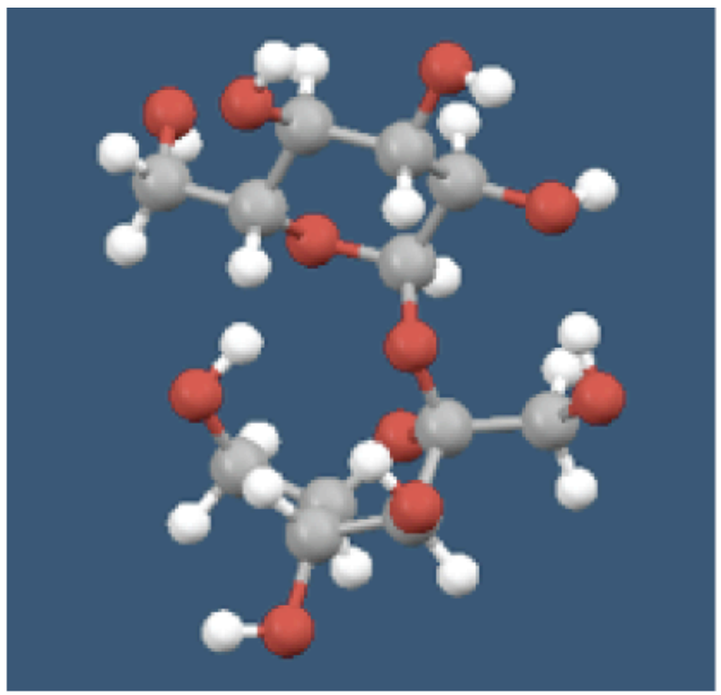


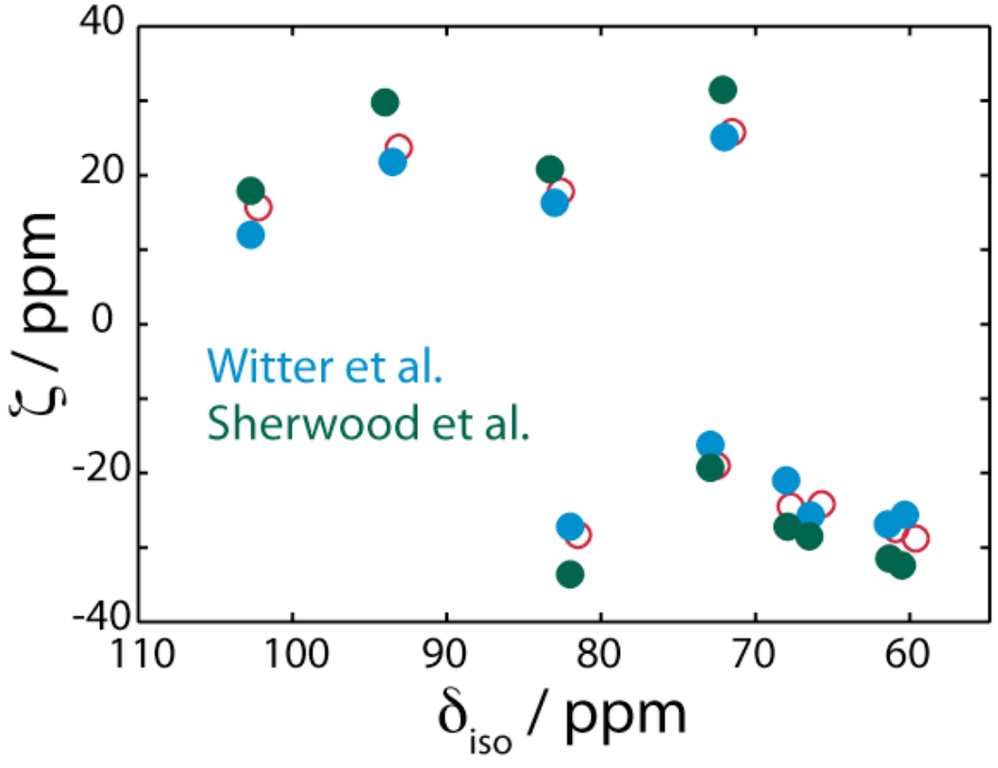
amplification: 8

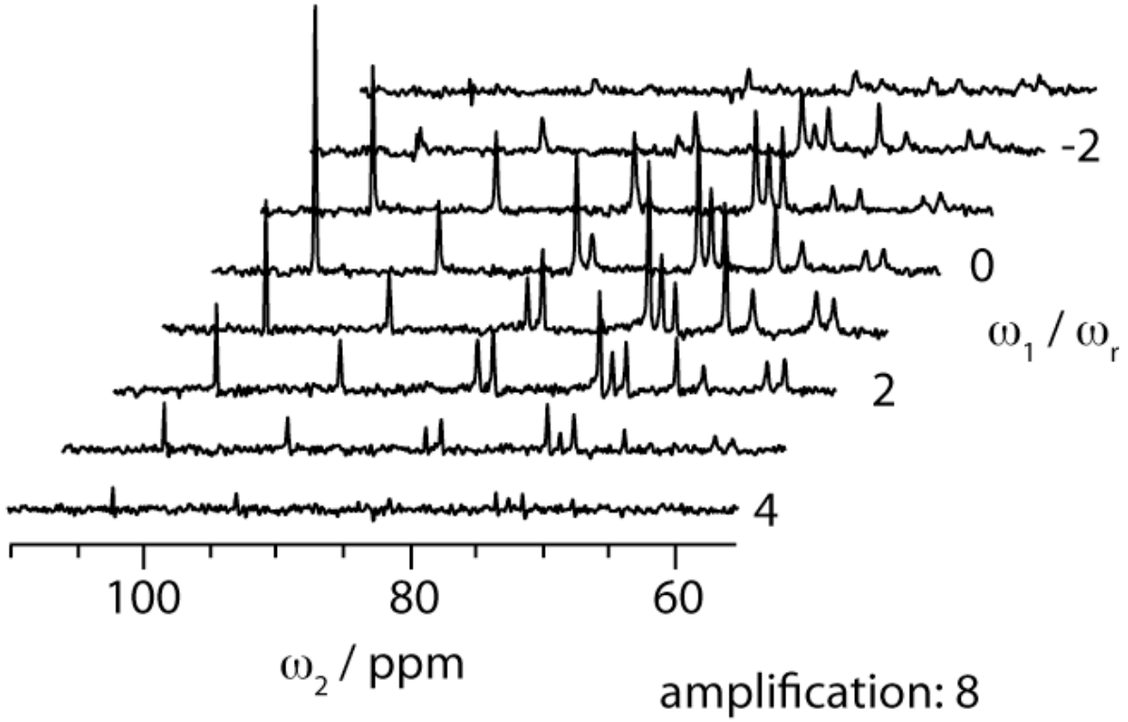
effective rate: 600 Hz

Validation of the CSA amplification method









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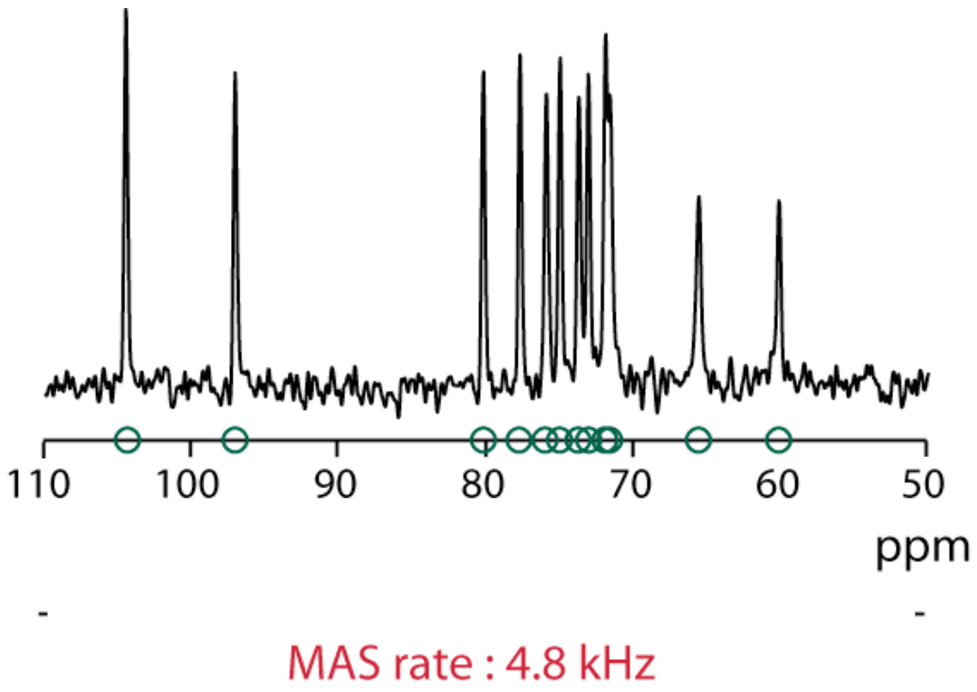
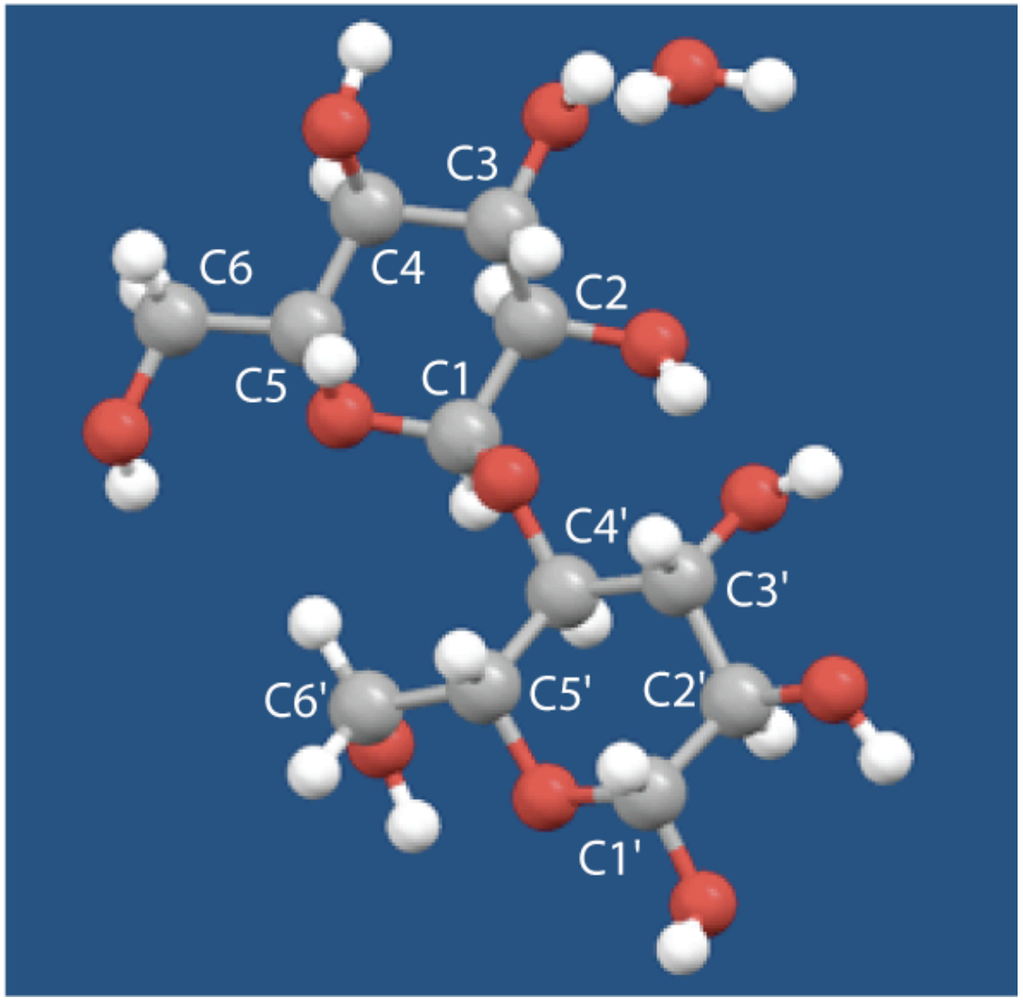
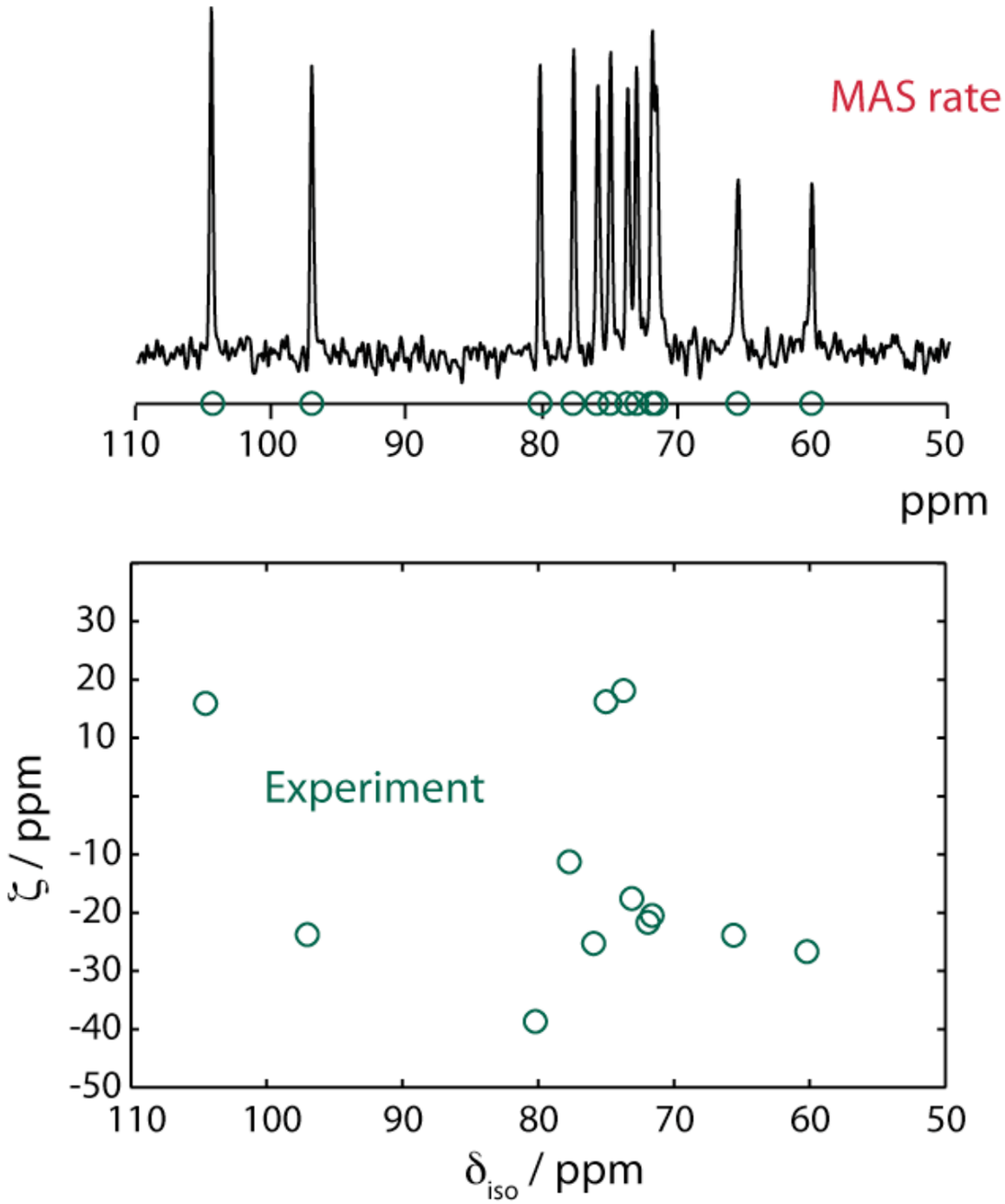
Maltose

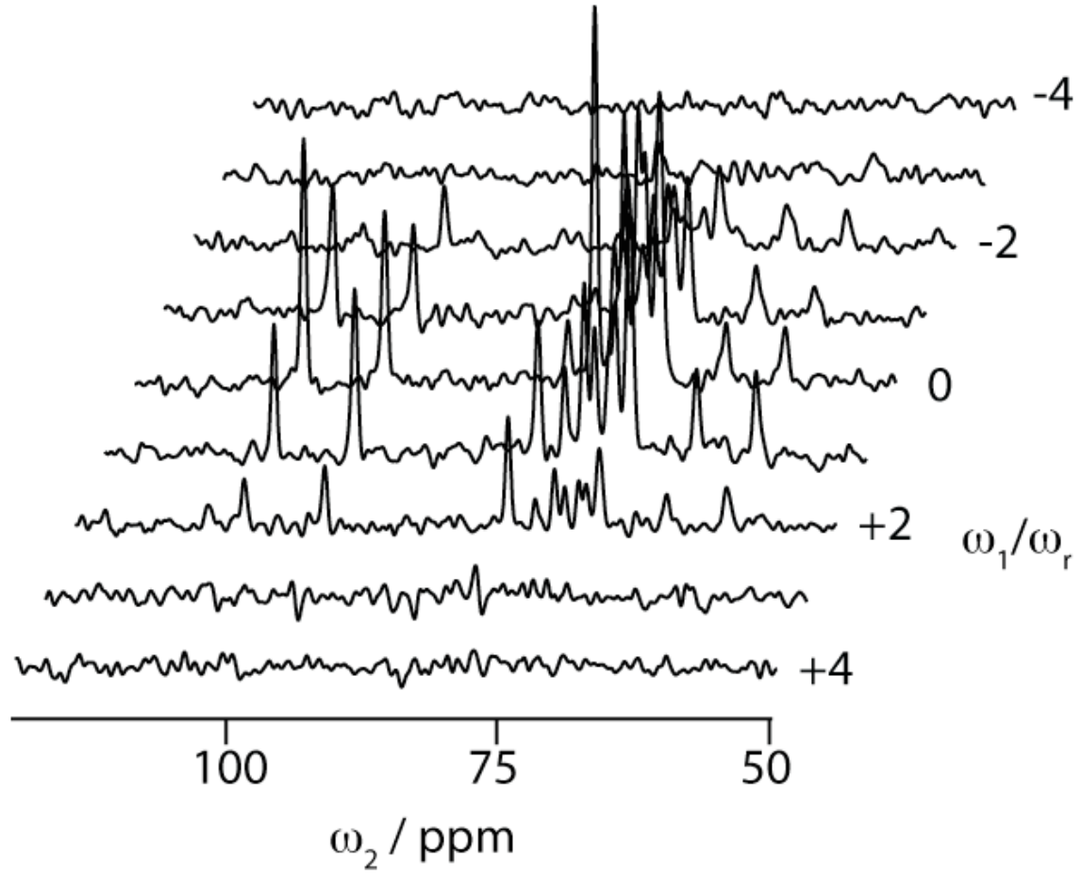




Poor shift dispersion in saccharides prevents assignment of carbon-13 spectrum

Shift anisotropies by CSA amplification



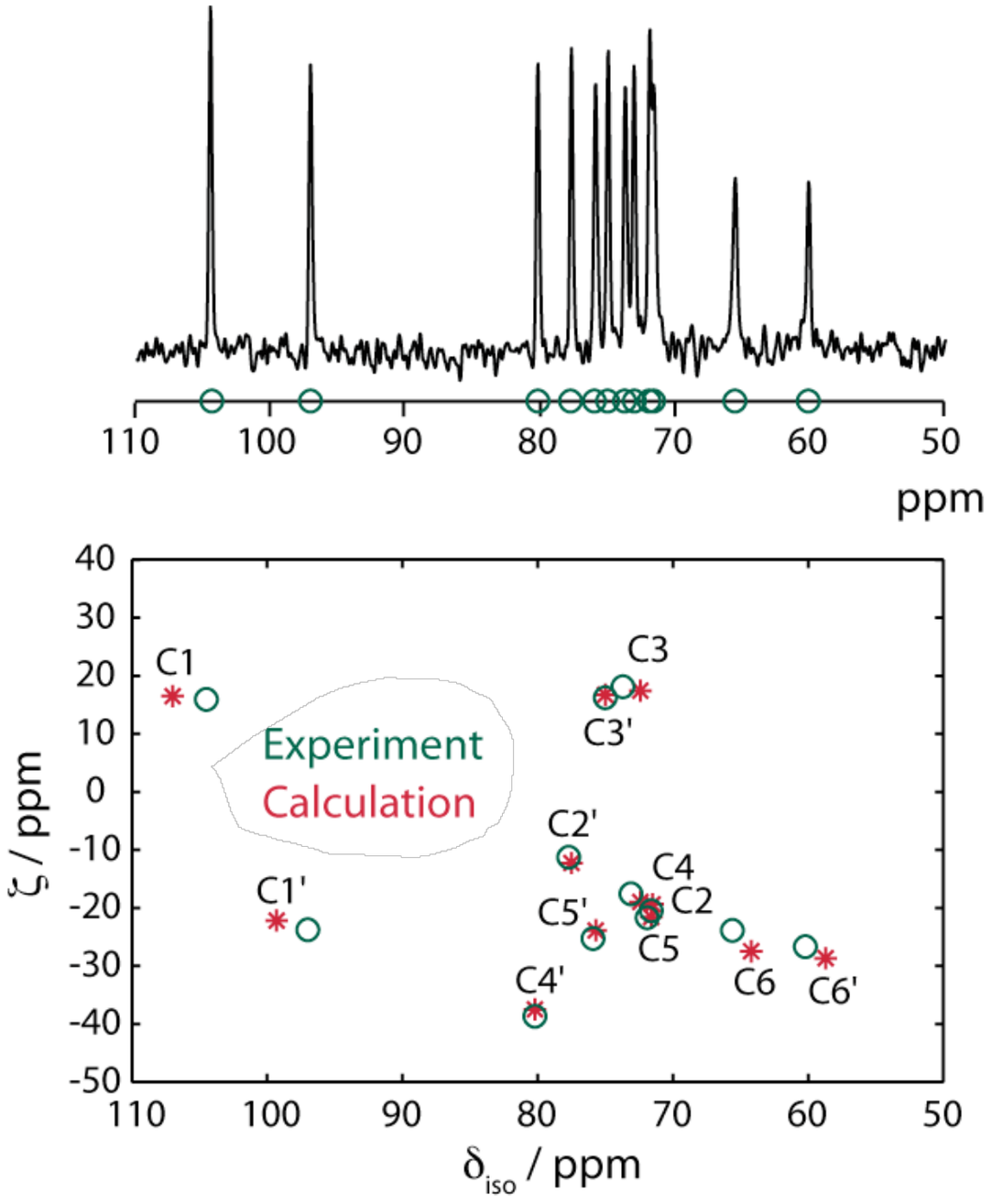


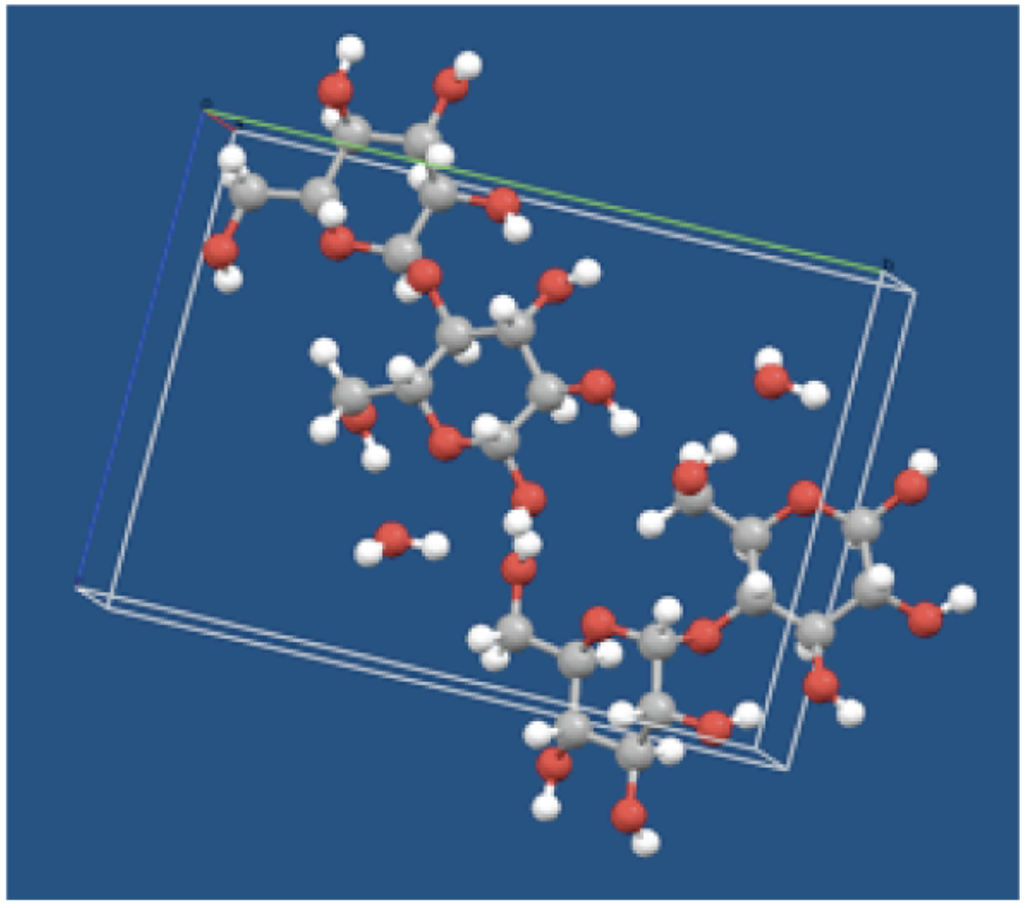
amplification : 8

effective rate : 600 Hz

Correlation of two shift parameters gives better resolution

Maltose: calculations and assignment





CASTEP/GIPAW

Combination with calculations allows assignment

L. Shao, J. Yates and J. J. Titman, *J. Chem. Phys. A*, **111,** 13126 (2007).

Summary

Two-dimensional **separation** experiments show spectra in the two dimensions which result from two different Hamiltonians.

Isotropic/anisotropic separation experiments are used to obtain the shift anisotropies of complicated molecules where overlap of powder patterns or sideband manifolds from different chemical sites prevents their measurement using a one-dimensional spectrum.

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