Welcome to the MagLab RM1 DNP workshop!

Sponsored by:

This workshop has received funding from the NIH under grant number RM1-GM148766.

PANACEA/NIH Maglab workshop

Introduction to Dynamic Nuclear Polarization

Concept/History/Applications

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NATIONAL HIGH MAGNETIC FIELD LABORATORY

NIH

NSF

GREAT SEAL OF THE STATE OF FLORIDA IN GOD WE TRUST

PANACEA

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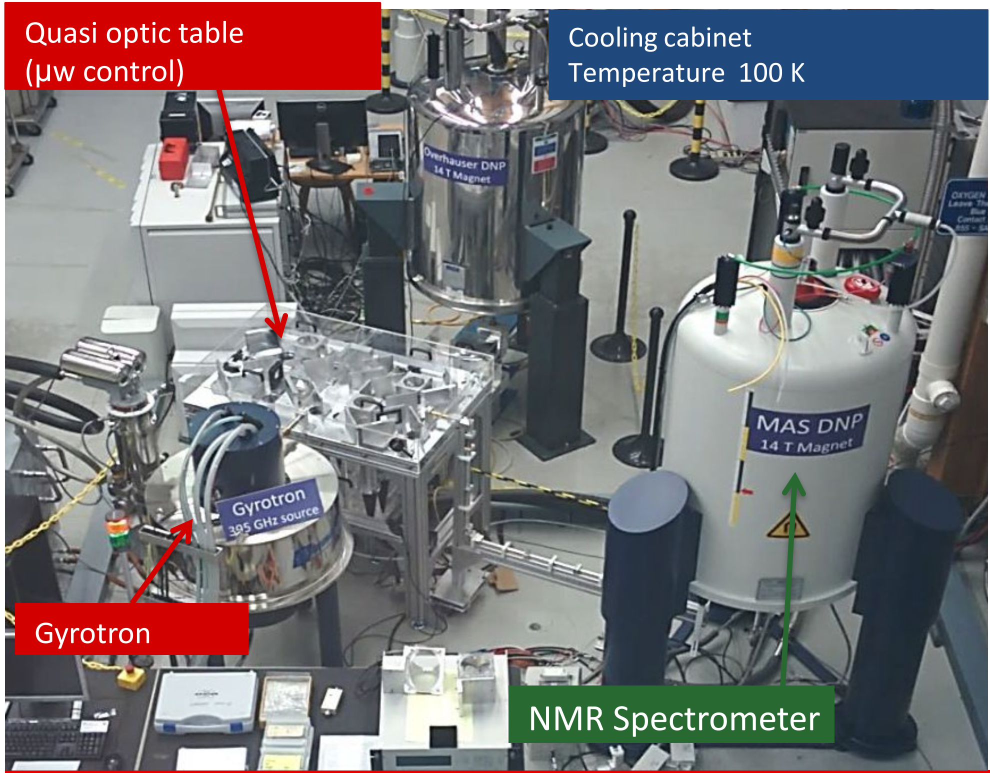
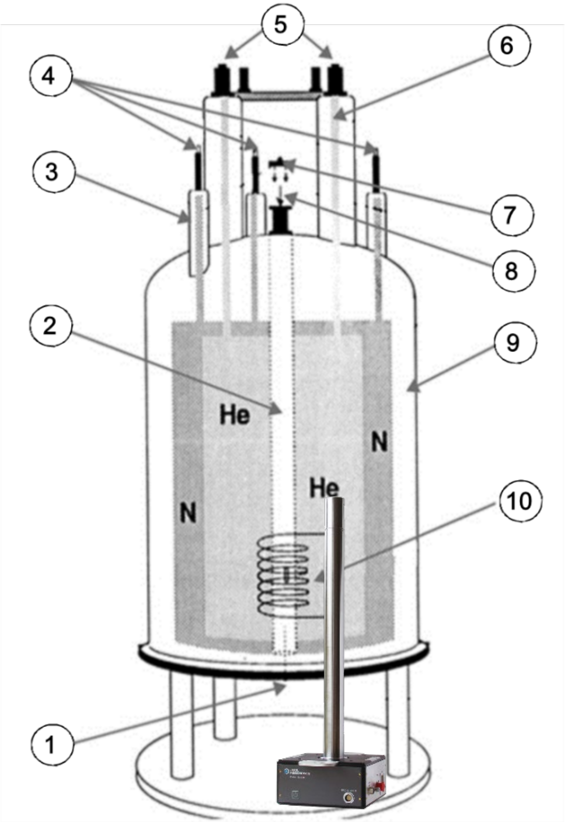
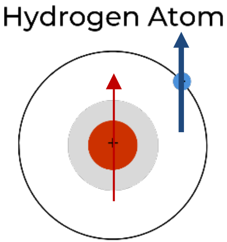


600 MHz MAS-DNP system in Tallahassee: User Program 08/16
https://users.magnet.fsu.edu

NMR in a nutshell





Big coil: creates the magnetic field

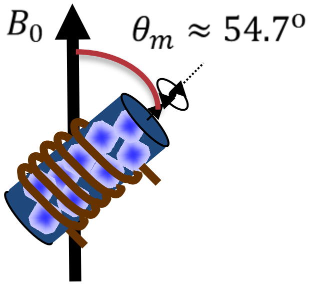
Proton spin = weak magnet

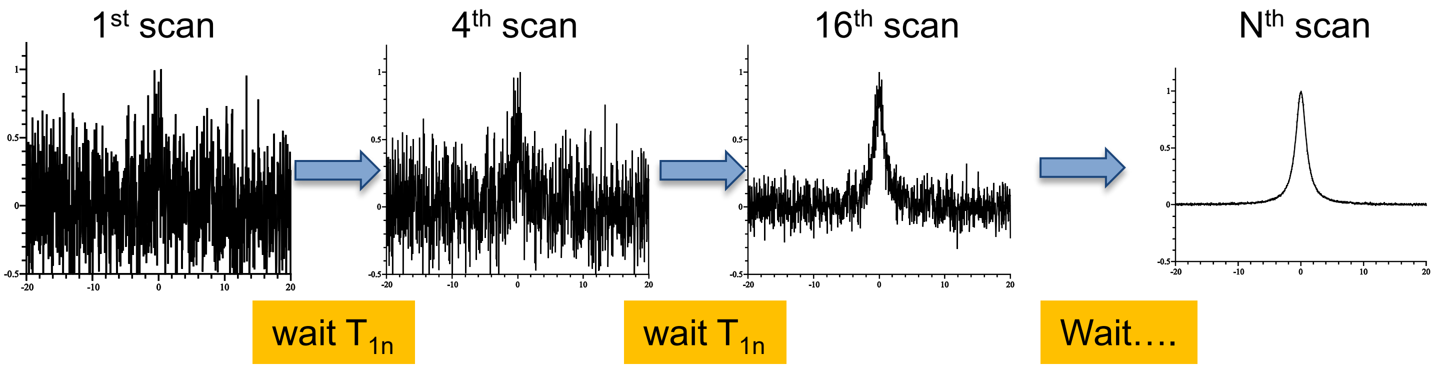
Probe: contains the sample and the detection setup

Nuclear Magnetic Resonance issues

- Nuclear magnetic resonance
  - High resolution even in solid state: Magic Angle Spinning (MAS)
    - structural information: material application
    - One chemical site = one resonance
    - Ease to manipulate spins
  - Low signal to noise:
    - Scan averaging for better signal/noise ratio
    - Complex study impossible at low natural abundance or surface

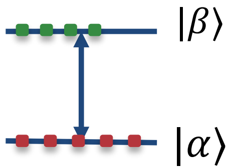
      → DNP Development





Nuclear and Electron Magnetic Resonance

- Spin under magnetic field

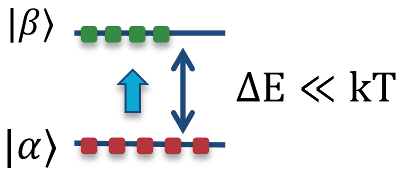


$$\Delta E = \gamma \hbar B_z$$

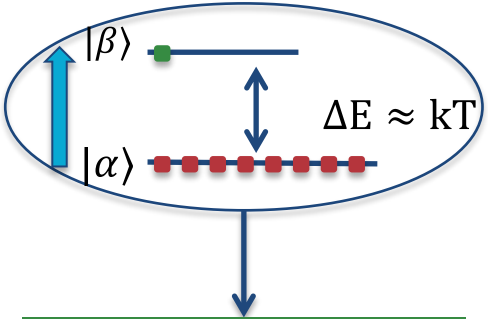
At thermal equilibrium, $k_B T \sim 6.25$ THz at RT

$$\hat{\rho} = e^{-\frac{\hat{H}_z}{k_B T}}, \quad \text{and} \quad P = \frac{N_{|\alpha\rangle} - N_{|\beta\rangle}}{N_{|\alpha\rangle} + N_{|\beta\rangle}} = \frac{e^{\frac{\Delta E}{2k_B T}} - e^{-\frac{\Delta E}{2k_B T}}}{e^{\frac{\Delta E}{2k_B T}} + e^{-\frac{\Delta E}{2k_B T}}}$$

- Assembly of spins: polarization and relaxation

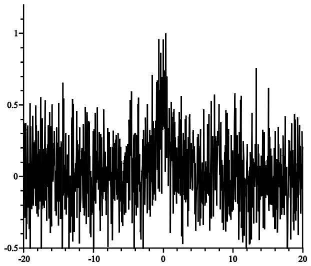


Weak Polarization
→ NMR

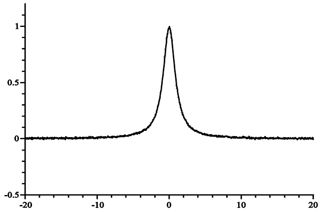


Strong Polarization →
optics, low Temp EPR

Majority of NMR experiments
→ low NMR signal
+ slow relaxation towards
equilibrium (T_{1n})



Routine condition in high field EPR
at low temperature
Fast relaxation toward equilibrium
(T_{1e})



Dynamic Nuclear Polarization:
combining EPR sensitivity with NMR exceptional resolution

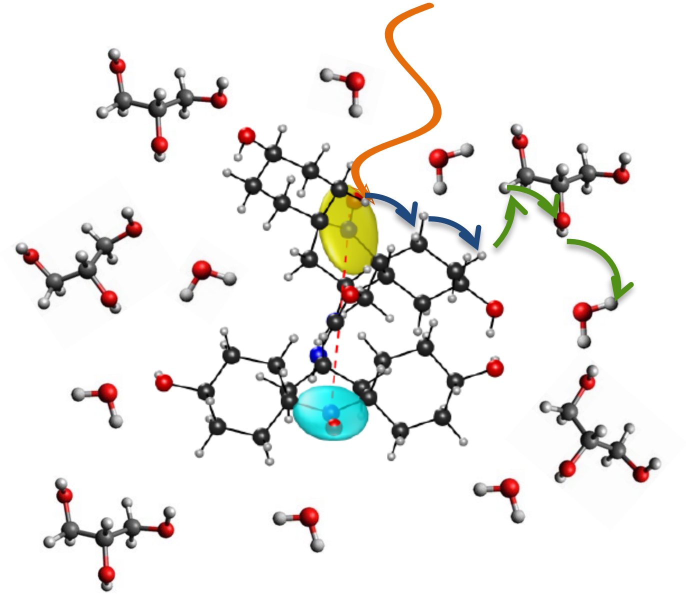
How does DNP "works*"

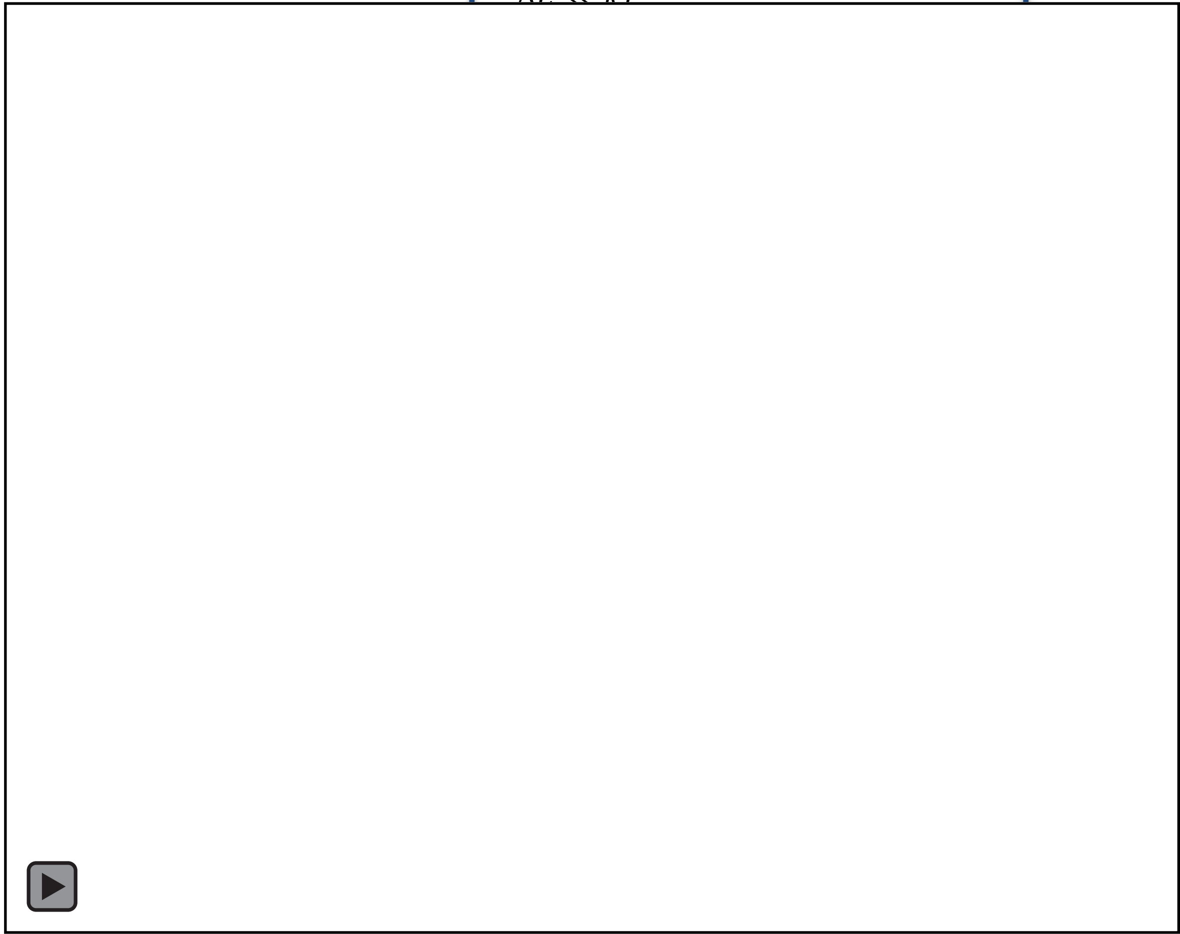
- * I will only focus on [^{1}H]

Microwave perturbs the radical polarization

Nuclear hyperpolarization is generated on local [^{1}H] and transferred to the surroundings

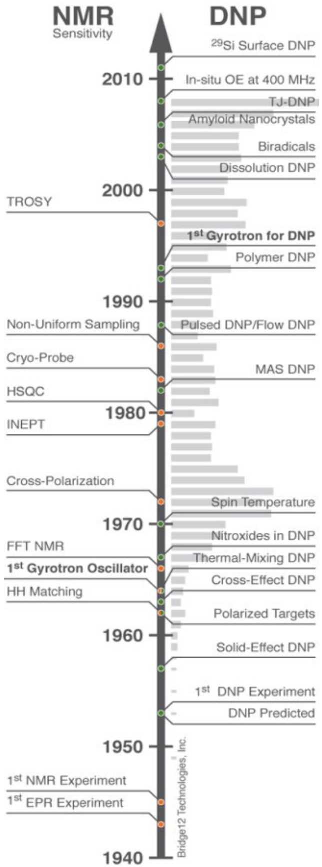
Then transferred to the surroundings





Historical aspect

Bridge12.com



- EPR: first experiment, then NMR

- Dynamic Nuclear polarization:
  - 1953: theoretical prediction by Overhauser [1] ~ 10 y later
  - Experimental demonstration by Carver and Slichter [2]

- First applications:
  - Polarization of targets for particle physics
  - Study fundamental mechanistic effect (Abragam, Goldman, Hwang, Borghini…)

- Development of DNP for NMR applications
  - From 1985 to now.

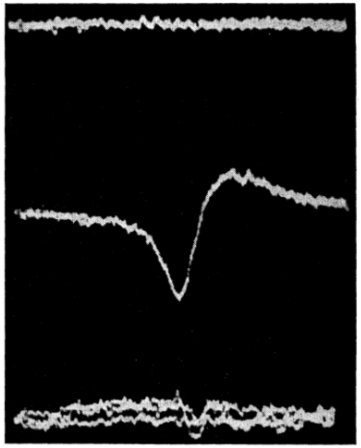
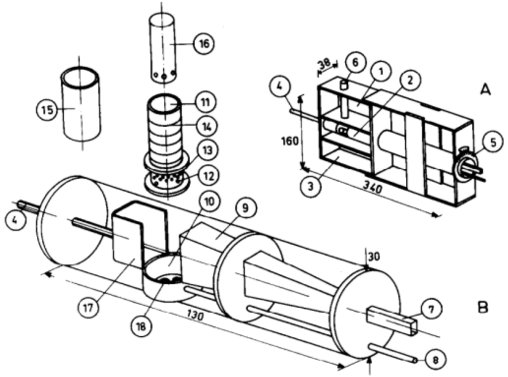


FIG. 1. Oscilloscope pictures of 50-kc/sec nuclear resonance absorption *vs* static magnetic field. Field excursion 0.2 gauss. Top line: Li^7 resonance (lost in noise). Middle line: Li^7 resonance enhanced by electron saturation. Bottom line: Proton resonance in glycerin sample.

(1) Overhauser, A. W. *Phys. Rev.* **1953**, *92*, 411.
(2) Carver, T. R.; Slichter, C. P. *Phys. Rev.* **1953**, *92*, 212.

Beginning of MAS-DNP

- First MAS-DNP
  - Wind, R. A.; Duijvestijn, M. J.; van der Lugt, C.; Manenschijn, A.; Vriend, J. *Prog. Nucl. Magn. Reson. Spectrosc.* **1985**, *17*, 33.



- Conditions:
  - Room temperature
  - 1.4 T electro-magnet (60 MHz, 40 GHz)
  - Microwave source → Klystron
  - First MAS-DNP system @3 kHz spinning frequency
- Aim
  - Study ^{13}C in coal samples
  - **Sensitivity is low + coal has unpaired (intrinsic radicals) electrons → DNP!**
  - **Note: low enhancements ~12**
- Other Applications
  - Study decomposition of Poly-Acetylene

R. A. Wind, M. J. Duijvestijn and J. Vriend, 1985, 56, 713–716.

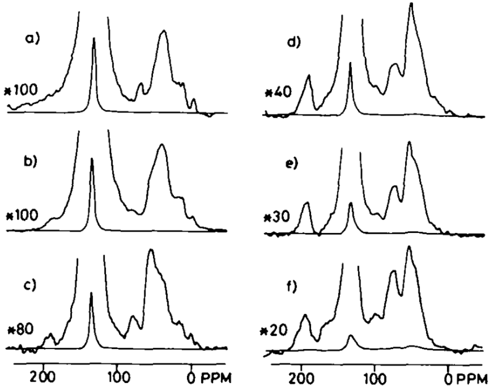


Fig. 1. ^{13}C NMR spectra obtained via DNP-CPMAS at different times after the rotor filling. a: 0.5 h; b: 13 h; c: 51 h; d: 98 h; e: 169 h; f: 4 months. The scale is given in ppm below TMS. The numbers denote the amplification factor of the spectrum. The signals without amplification are displayed in such a way that the integral is constant for all measurements. The following experimental conditions were used: match time = 1 ms; match field = 45 kHz; acquisition time = 26 ms; ^{1}H decoupling field = 70 kHz; recycle delay = 0.3 s; number of scans = 10,000 (a and b), 20,000 (c, d and e) and 30,000 (f); a Lorentzian broadening of 30 Hz is applied.

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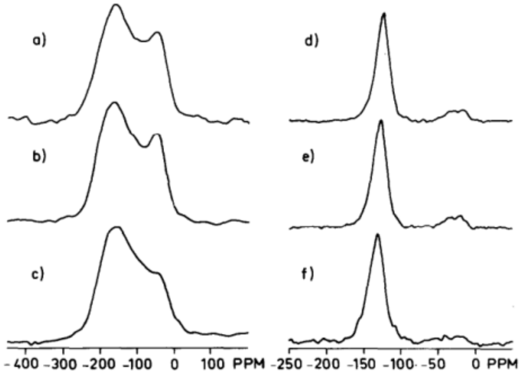
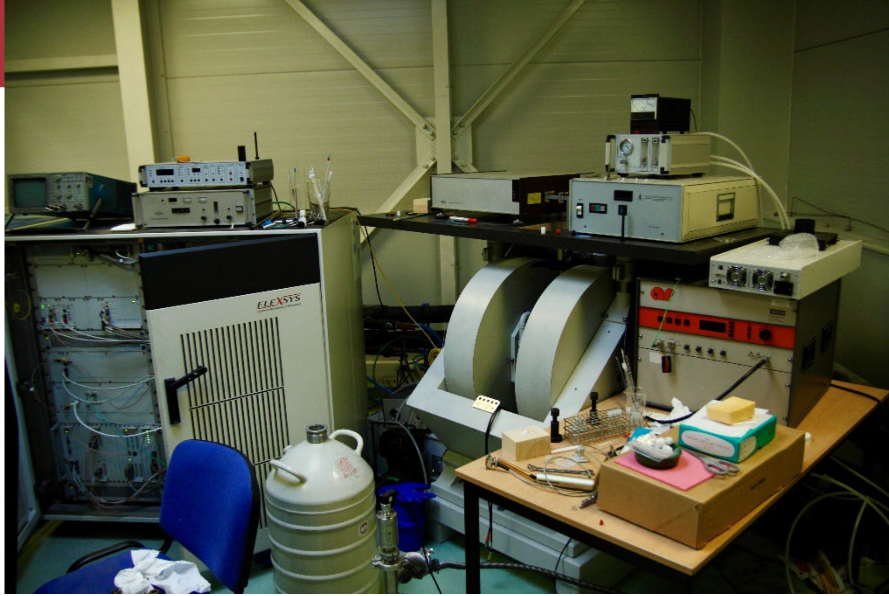


FIG. 14. ^{13}C spectra of a low volatile bituminous coal (20 % volatile matter, 90.2 % C, 4.6 % H, 3.8 % O (dmmf)) obtained via different methods. (a) via CP. Match time = 0.9 msec; acquisition time = 5 msec; match field = proton decoupling field = 50 KHz; number of scans = 90,000; recycle delay = 0.6 sec. A Lorentzian broadening of 200 Hz is applied. (b) via DNP–CP. Proton enhancement = 29; number of scans = 200. Other parameters as in (a). (c) via DNP–FID. Carbon enhancement = 200; duration $\pi/2$ pulse = 6 μsec; acquisition time = 5 msec; proton decoupling field = 50 KHz; number of scans = 8; recycle delay = 60 sec; Lorentzian broadening = 200 Hz; (d) via CPMAS. Spinning frequency = 3.5 KHz; acquisition time = 15 msec; number of scans = 72,000; no broadening is used. Other parameters as in (a). (e) via DNP–CPMAS. Proton enhancement = 12; number of scans = 500. Other parameters as in (d). (f) via DNP–FIDMAS. Carbon enhancement = 150; spinning frequency = 3.5 KHz; acquisition time = 15 msec; number of scans = 4; recycle delay = 60 sec. Other parameters as in (c).

Beginning of MAS-DNP



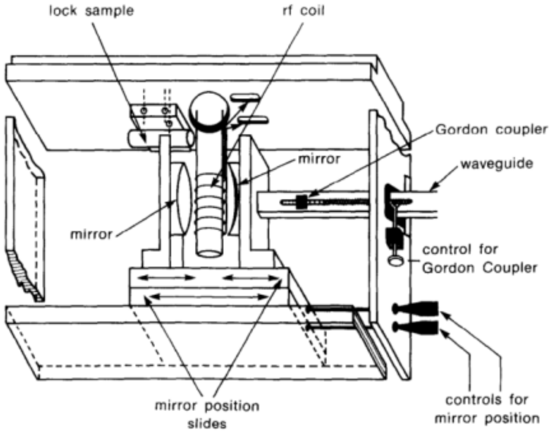
- First MAS-DNP
  - Wind, R. A.; Duijvestijn, M. J.; van der Lugt, C.; Manenschijn, A.; Vriend, J. *Prog. Nucl. Magn. Reson. Spectrosc.* **1985**, *17*, 33.
- Conditions:
  - Room temperature
  - 1.4 T electro-magnet (60 MHz, 40 GHz)
  - Microwave source → Klystron
  - First MAS-DNP system @3 kHz spinning frequency
- Aim
  - Study ^{13}C in coal samples
  - **Sensitivity is low + coal has unpaired (intrinsic radicals) electrons → DNP!**
  - **Note: low enhancements ~12**
- Other Applications
  - Study decomposition of Poly-Acetylene

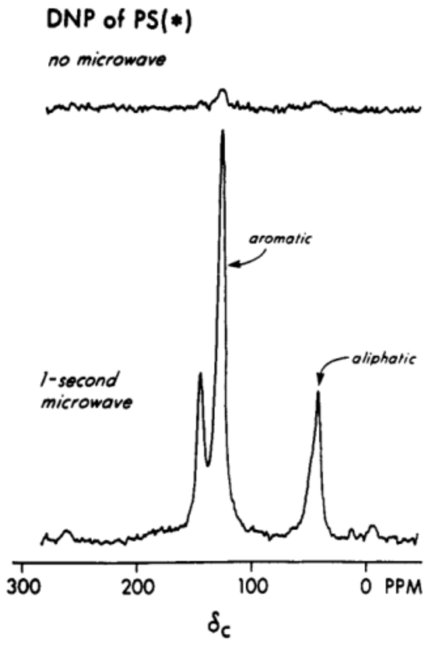
Beginning of MAS-DNP

- Other groups: Yannoni and Schafer
  - Similar setups:
    1.4T (^{1}H = 60 MHz, e = 40 GHz)
  - Variations on the way the mw is handled
    Transverse irradiation + Fabry Perrot resonator (Yannoni)
  - Longitudinal irradiation (Schaeffer)

(1) Singel, D. J.; Seidel, H.; Kendrick, R. D.; Yannoni, C. S. J. Magn. Reson. 1989, 81, 145.
(2) Afeworki, M.; Vega, S.; Schaefer, J. Macromolecules 1992, 25, 4100.

- Applications: Material Science
  - Electron spin's source:
    - doping with BDPA
    - intrinsic radicals: islands of polyacetylene embedded in a matrix of polyethylene.
  - Some Results
    - Interface Polycarbonate/Poly-Styrene





High-Field Breakthrough

- Griffin and Temkin's: 1993 **[1]**
  - Supra-conductive magnet → 5 T
  - mw source: Gyrotron MASER @140 GHz
  - Sample: BDPA Polystyrene

(1) Becerra, L. R.; Gerfen, G. J.; Temkin, R. J.; Singel, D. J.; Griffin, R. G. *Phys. Rev. Lett.* **1993**, *71*, 3561.

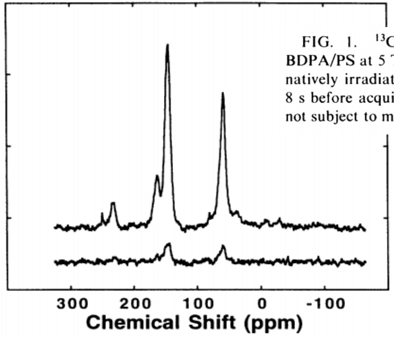


FIG. 1. ^{13}C cross-polarization MAS spectrum of (2%) BDPA/PS at 5 T and room temperature. The sample was alternatively irradiated with 139.6 GHz microwaves at $\omega_e - \omega_H$ for 8 s before acquisition of the DNP enhanced spectrum (top), or not subject to microwave irradiation (bottom).

- Path towards modern MAS-DNP
  - 1995: frozen solution and static condition [2] Tempo+Glycerol/H_2O mixture
  - 1997 First "bio" application under MAS [3]

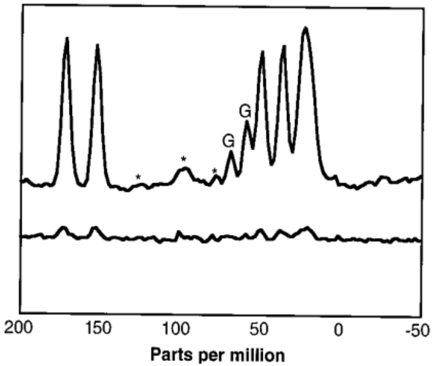


Fig. 2. DNP-CP ^{13}C solid-state MAS (3.0 kHz spin rate) spectra of fully ^{13}C-^{15}N–labeled L-Arg (30 mg/ml Arg and 40 mM 4-amino-TEMPO in 60:40 water-glycerol) at 55 K. The peaks labeled with an asterisk correspond to rotational sidebands and those labeled G correspond to the natural abundance ^{13}C glycerol peaks. Microwave irradiation (139.60 GHz) was performed for 15 s with ~1 W at the sample. Sixteen acquisitions were averaged with a 1-s recycle delay. The bottom spectrum was recorded under identical conditions with no microwave power. The magnetic field was set to maximize the positive enhancement, which is approximately 20.

(2) Gerfen, G. J.; Becerra, L. R.; Hall, D. A.; Griffin, R. G.; Temkin, R. J.; Singel, D. J. *J. Chem. Phys.* **1995**, *102*, 9494.
(3) Hall, D. A.; Maus, D. C.; Gerfen, G. J.; Inati, S. J.; Becerra, L. R.; Dahlquist, F. W.; Griffin, R. G. *Science* **1997**, *276*, 930.

High-Field Breakthrough

- Path towards modern MAS-DNP
  - 1995: frozen solution and static condition **[2]**
    Tempo+Glycerol/H_2O mixture
  - 1997 First "bio" application under MAS **[3]**
  - 2004 biradicals
  - ***2009: First Bruker 400 MHz/263 GHz commercial system.***

Many developments since

65 kHz MAS-DNP

900 MHz MAS-DNP

NA ^{13}C-^{15}N Correlation

Quantitative simulation

NA HETCOR

40 kHz MAS-DNP

Trityl-Nitroxide

Various Applications

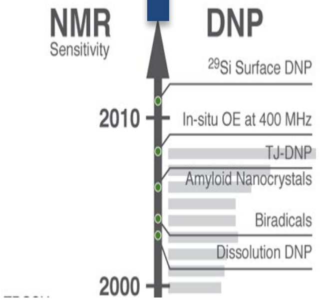
800 MHz MAS-DNP

NA ^{13}C-^{13}C Correlation

Real Sensitivity?

MAS-DNP Theory

Surface ^{27}Al MQMAS



Dynamic Nuclear Polarization… today

- Growing community
  - About 25 instruments installed since 2010
  - More to be installed…

- Extremely active field
  - Lot of credit to R.G. Griffin/Temkin (bringing MAS to high-field and modern methods)
  - Initial/continuous material applications work by:
    - G. Bodenhausen, O. Lafon
      L. Emsley, M. Pruski, G. De Paepe's groups (I hope I'm not forgetting anyone)
  - Lot of ongoing instrument development (some examples)

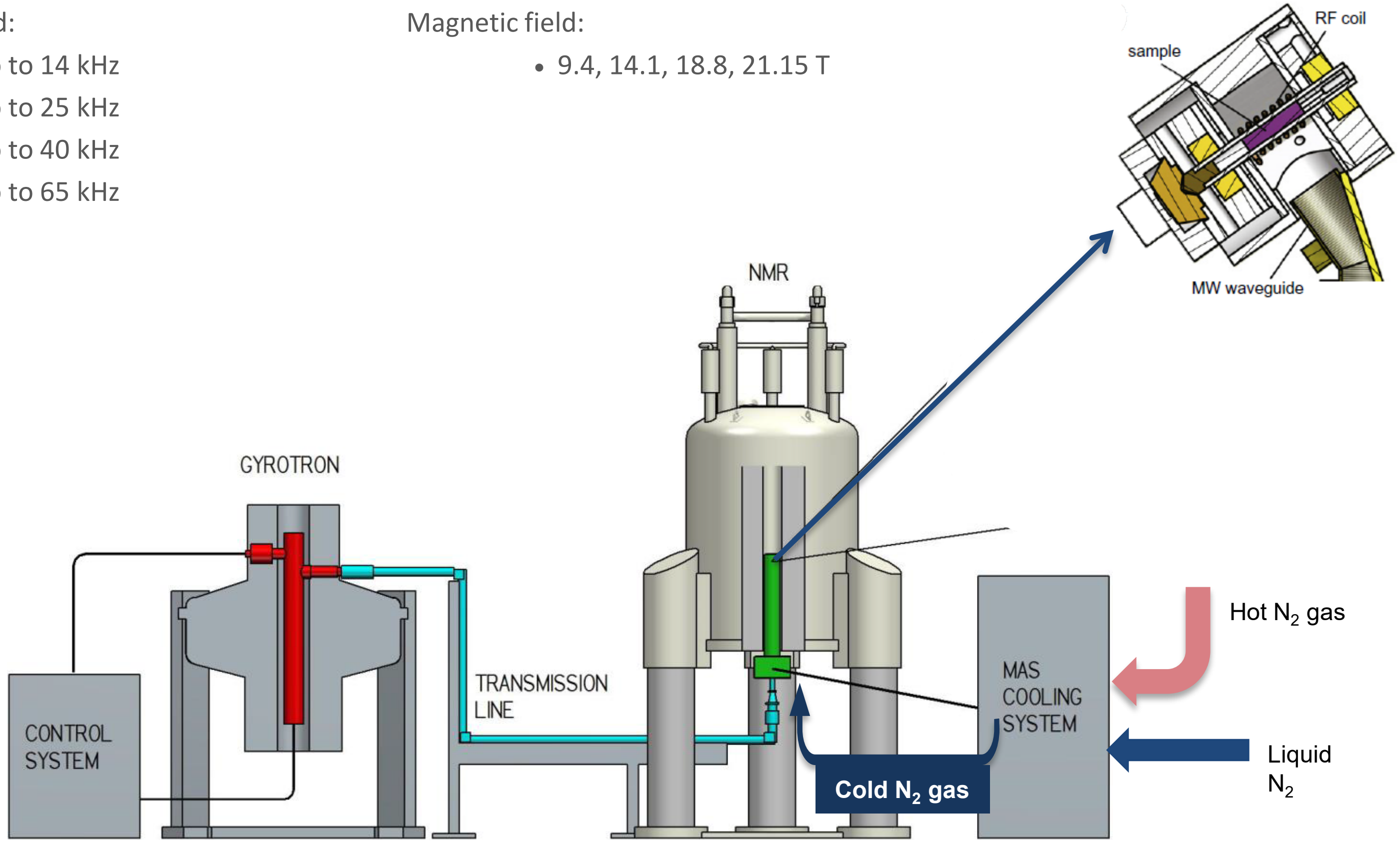
Ultra low temperature (He spinning) →
- De Paepe (CEA)
- Thurber/Tycko (NIH)
- Fujiwara (Osaka)
- Barnes (WashU)

Higher temperature → Emsley/Lesage/Lelli (EPFL/Lyon)

Pulse DNP → MIT (Griffin, ENS, Konstanz)

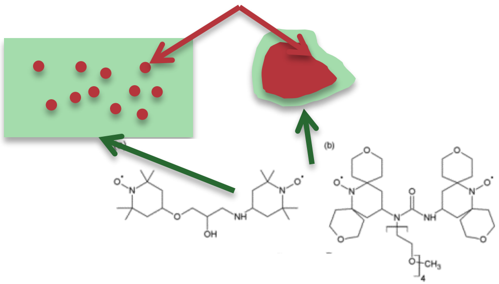
Dynamic Nuclear Polarization… today

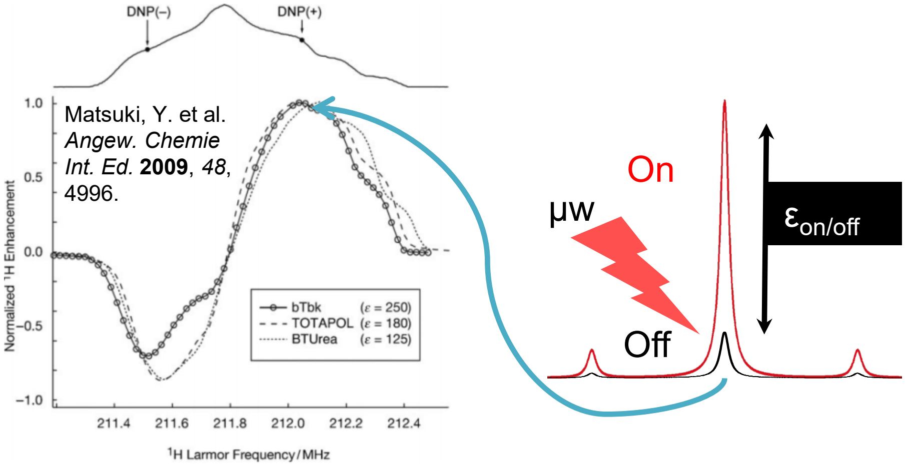
- Commercial MAS-DNP spectrometer (M. Rosay/R.G. Griffin)
  - Sample temperature from 100 K to RT
  - Spinning speed:
    - 3.2 mm → up to 14 kHz
    - 1.9 mm → up to 25 kHz
    - 1.3 mm → up to 40 kHz
    - 0.7 mm → up to 65 kHz
  - Magnetic field:
    - 9.4, 14.1, 18.8, 21.15 T

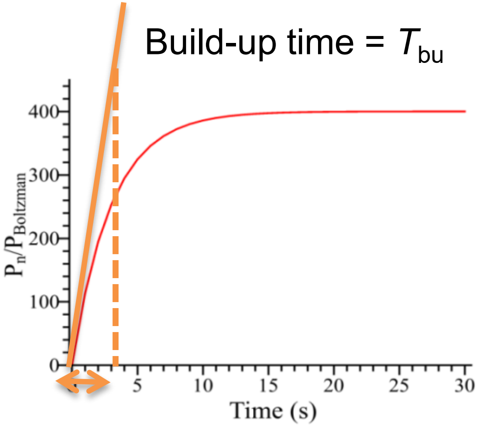


MAS-DNP Experiment

- MAS-DNP Routine setup
  - Paramagnetic center + uw + target → NMR signal enhancement
  - Radical in glass forming solvent or impregnation
    - Glycerol/water,
    - DMSO/Water,
    - TCE
  - Electrons polarization source
    - biradical = bis-nitroxide TOTAPOL, AMUPol, bTbK, Tekpol…



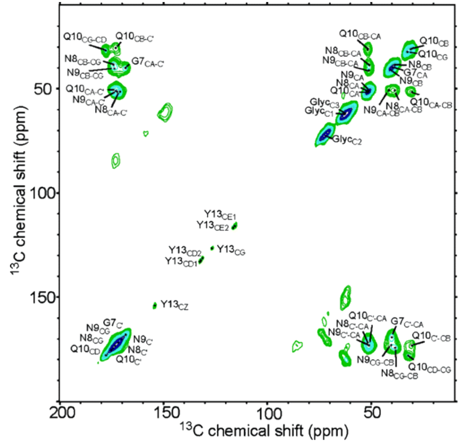




First biological applications: microcrystals and Amyloids

- ^{13}C-^{13}C isotopically enriched, Amyloids

P. C. A. van der Wel, K.-N. Hu, J. Lewandowski and R. G. Griffin, Dynamic Nuclear Polarization of Amyloidogenic Peptide Nanocrystals: GNNQQNY, a Core Segment of the Yeast Prion Protein Sup35p, J. Am. Chem. Soc., 2006, 128, 10840–10846.



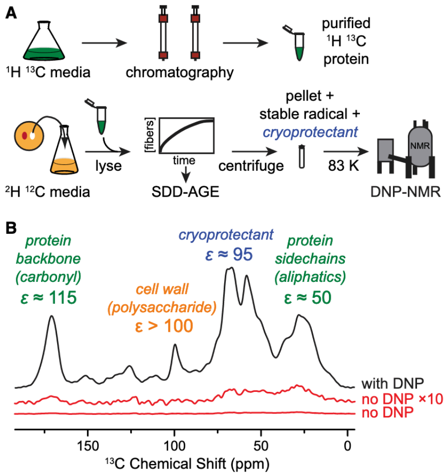
Aim: demonstrate application of DNP to amyloids

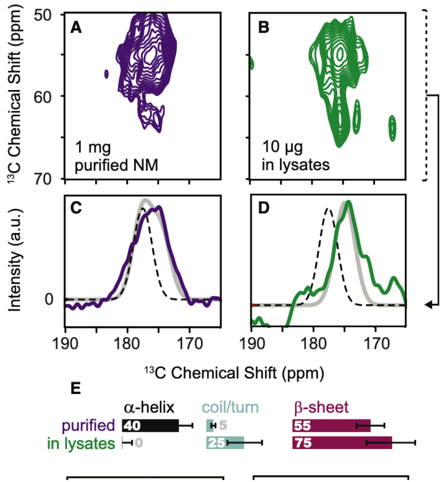
Challenge: demonstrate applicability of DNP to bio relevant question

Sample: GNNQQNY nanocrystallites
Biradical:Totapol + d8-glycerol/d2o/H2O

- Application in-cell (2015)

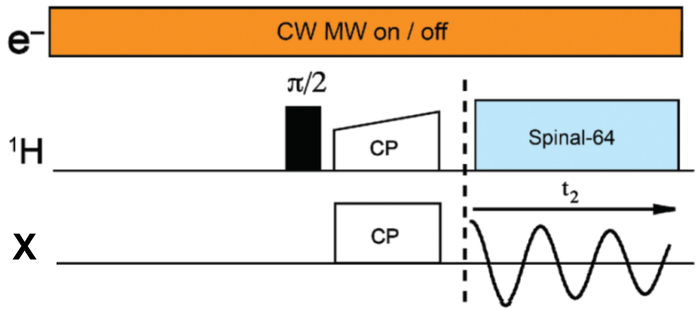
K. K. Frederick, V. K. Michaelis, B. Corzilius, T.-C. Ong, A. C. Jacavone, R. G. Griffin and S. Lindquist, Sensitivity-Enhanced NMR Reveals Alterations in Protein Structure by Cellular Milieus, Cell, 2015, 163, 620–628.





Surface Enhanced DNP

- Initial application for DNP
  - Aim: detect surface properties
  - Still widely used (also called DNP-SENS)



- Method:
  - Polarize protons → CP transfer to target
  - Work with Natural Abundance isotopes
  - Use « Impregnation methods »

- First targets (2010 – 2014)

^{27}Al Catalytic properties

^{13}C Molecule grafted on functionalized materials

^{29}Si on nanostructured materials

Not talking about bio applications

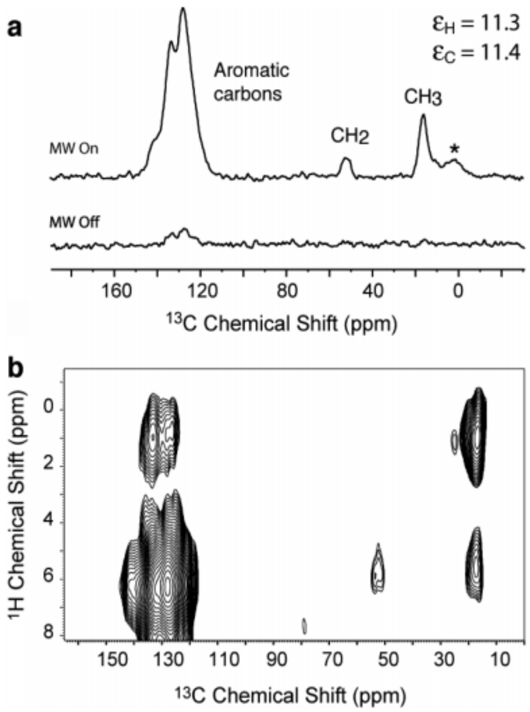
Surface Enhanced DNP (^{13}C)

- Emsley + Bodenhausen **2010**

Pioneer Meso-Porous application:
Detection of natural abundance
surface signal Phenol grafted on mesoporous silica (6 nm pores)

Lesage, A.; Lelli, M.; Gajan, D.; Caporini, M. A.; Vitzthum, V.; Miéville, P.; Alauzun, J.; Roussey, A.; Thieuleux, C.; Mehdi, A.; Bodenhausen, G.; Coperet, C.; Emsley, L. *J. Am. Chem. Soc.* **2010**, *132*, 15459.

Sample:
Radical = TOTAPOL
Solvent = D_2O/H_2O
Field 9.4T



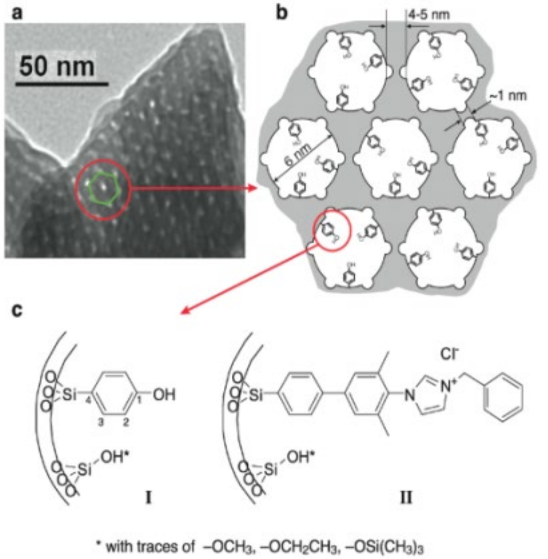


Figure 1. (a) Transmission electronic microscopy image of the nanoporous silica material. (b) Schematic representation of the pore [mesopores (6 nm diameter) are shown as circles and micropores (<1 nm diameter) as small half-circles] and channel network with phenol functionalities. The shaded gray area represents the silica bulk. (c) Different covalently incorporated aromatic substrates.

Surface Enhanced DNP (^{13}C, ^{15}N, ^{29}Si)

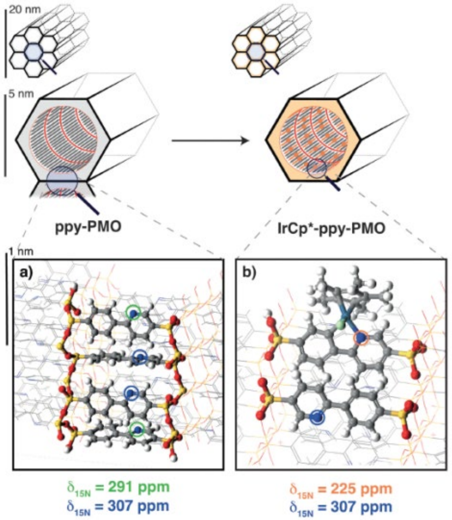
- Surface analysis

Grüning, W. R.; Rossini, A. J.; Zagdoun, A.; Gajan, D.; Lesage, A.; Emsley, L.; Copéret, C. Phys. Chem. Chem. Phys. 2013, 15 (32), 13270.

Aim: Confirm functionalization + structure

Challenge: perform Surface ^{15}N, ^{13}C and ^{29}Si analysis (HETCOR)

Sample: Periodic mesoporous organosilicates
Radical = bCTbK – Solvent = TCE



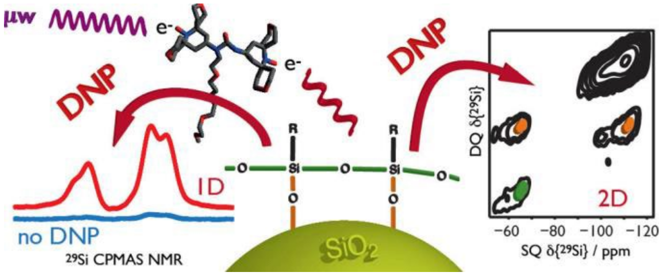
- Silicon-Silicon correlations

Lee, D.; Monin, G.; Duong, N. T.; Lopez, I. Z.; Bardet, M.; Mareau, V.; Gonon, L.; De Paëpe, G. J. Am. Chem. Soc. 2014, 136 (39), 13781–13788.

Aim: Reveal the condensation mechanism

Challenge: perform 2D ^{29}Si-^{29}Si Correlation at natural abundance (SR26/Refocused INADEQUATE)

Sample: Polyethylsiloxane functionalized NPs
Radical = AMUPol – Solvent = DMSO/H_2O



Surface Enhanced DNP (^{27}Al)

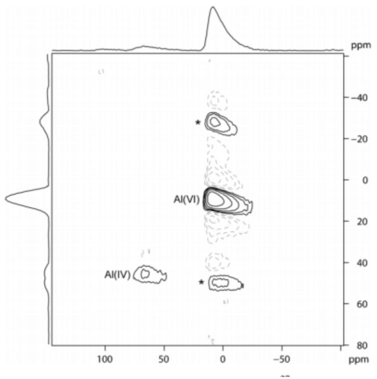
- γ Alumina

Vitzthum, V.; Miéville, P.; Carnevale, D.; Caporini, M. A.; Gajan, D.; Copéret, C.; Lelli, M.; Zagdoun, A.; Rossini, A. J.; Lesage, A.; Emsley, L.; Bodenhausen, G. Chem. Commun. 2012, 48, 1988.

Aim: Determine local symmetries of ^{27}Al

Challenge: run MQ MAS in less than a week (50 h)

Sample: γ alumina
Radical = TOTAPOL – Solvent = D_2O/H_2O



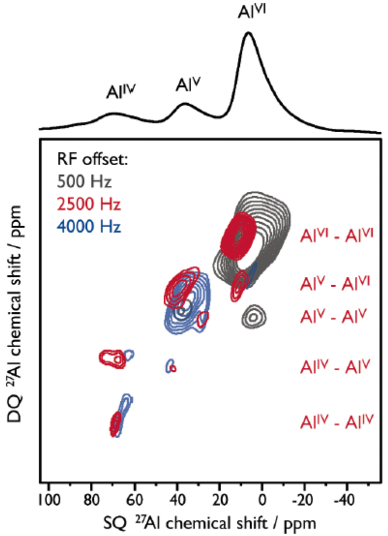
- Mesoporous Alumina

Lee, D.; Takahashi, H.; Thankamony, A. S. L.; Dacquin, J.-P.; Bardet, M.; Lafon, O.; Paëpe, G. De. J. Am. Chem. Soc. 2012, 134 (45), 18491–18494.

Aim: determine local symmetries of ^{27}Al and connectivity

Challenge: run MQ MAS in a human time-scale (here 4h)

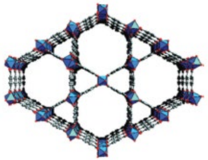
Sample: mesoporous alumina
Radical = TOTAPOL – Solvent = $DMSO/H_2O$

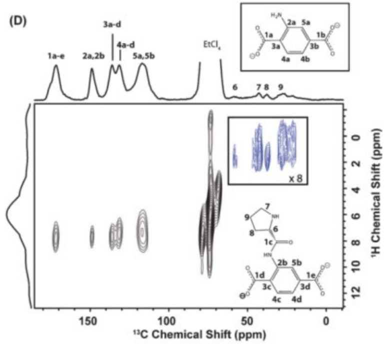


Functionalized Metal-Organic Frameworks

- MOF's

Rossini, A. J.; Zagdoun, A.; Lelli, M.; Canivet, J.; Aguado, S.; Ouari, O.; Tordo, P.; Rosay, M.; Maas, W. E.; Copéret, C.; Farrusseng, D.; Emsley, L.; Lesage, A. Angew. Chemie Int. Ed. 2012, 51, 123.





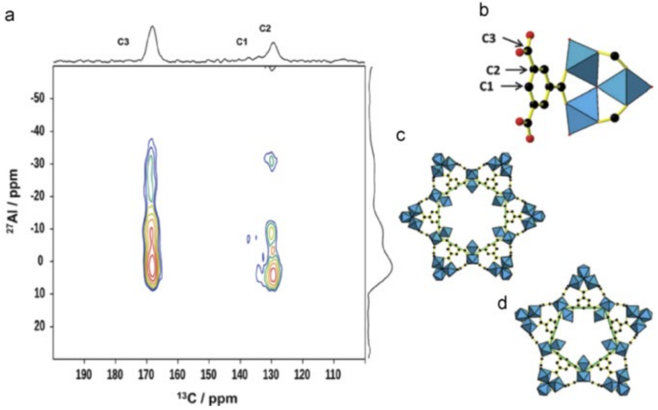
Aim: demonstrate applicability of DNP to MOFs

Challenge: enhance signals in the pores (HETCOR)

Sample: N-functionalized MOFs
Radical = bTbK – Solvent = TCE

- ^{27}Al-^{13}C correlations

Pourpoint, F.; Thankamony, A. S. L.; Volkringer, C.; Loiseau, T.; Trébosc, J.; Aussenac, F.; Carnevale, D.; Bodenhausen, G.; Vezin, H.; Lafon, O.; Amoureux, J.-P. Chem. Commun. 2014, 50 (8), 933–935.



Aim: demonstrate applicability of DNP to MOFs

Challenge: Probe Al-C connectivity/proximity (HETCOR)

Sample: metal–organic framework MIL-100(Al) Radical = TOTAPOL – Solvent = H_2O

Other Material Applications

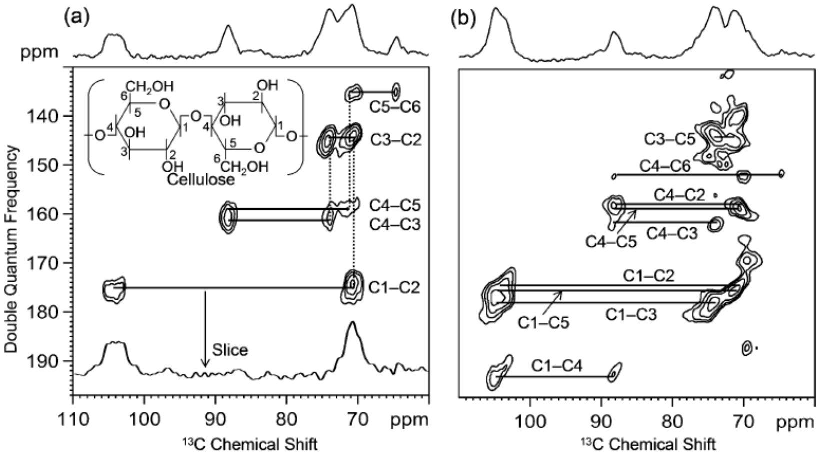
- Nano/mesoparticles

Takahashi, H.; Lee, D.; Dubois, L.; Bardet, M.; Hediger, S.; De Paëpe, G. Angew. Chemie Int. Ed. 2012, 51 (47), 11766–11769.

Aim: demonstrate Natural Abundance ^{13}C-^{13}C correlation

Challenge: run Refocussed Inadequate and POST-C7 in less than 20 minutes each

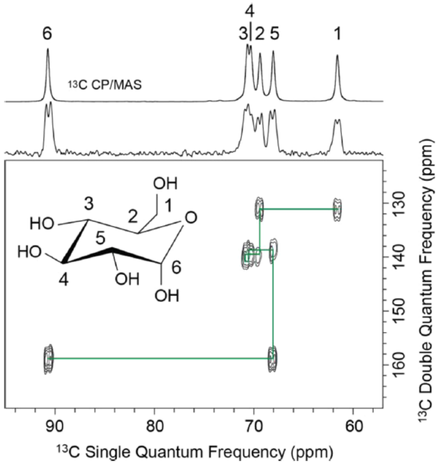
Sample: microcrystaline cellulose
Radical = TOTAPOL – Solvent = Matrix free



Rossini, A. J.; Zagdoun, A.; Hegner, F.; Schwarzwälder, M.; Gajan, D.; Copéret, C.; Lesage, A.; Emsley, L. J. Am. Chem. Soc. 2012, 134 (40), 16899–16908.

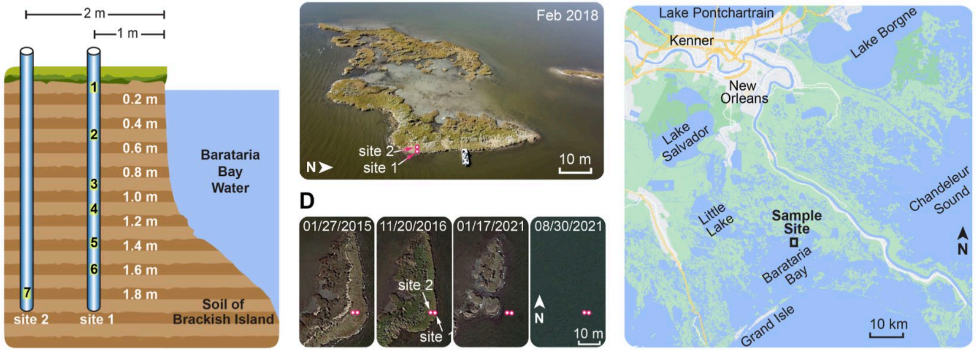
Challenge: determine local ^{13}C connectivity's (refocussed Inadequate) → 16 h

Sample: microcrystalline cellulose
Radical = bCTbk – Solvent = TBE

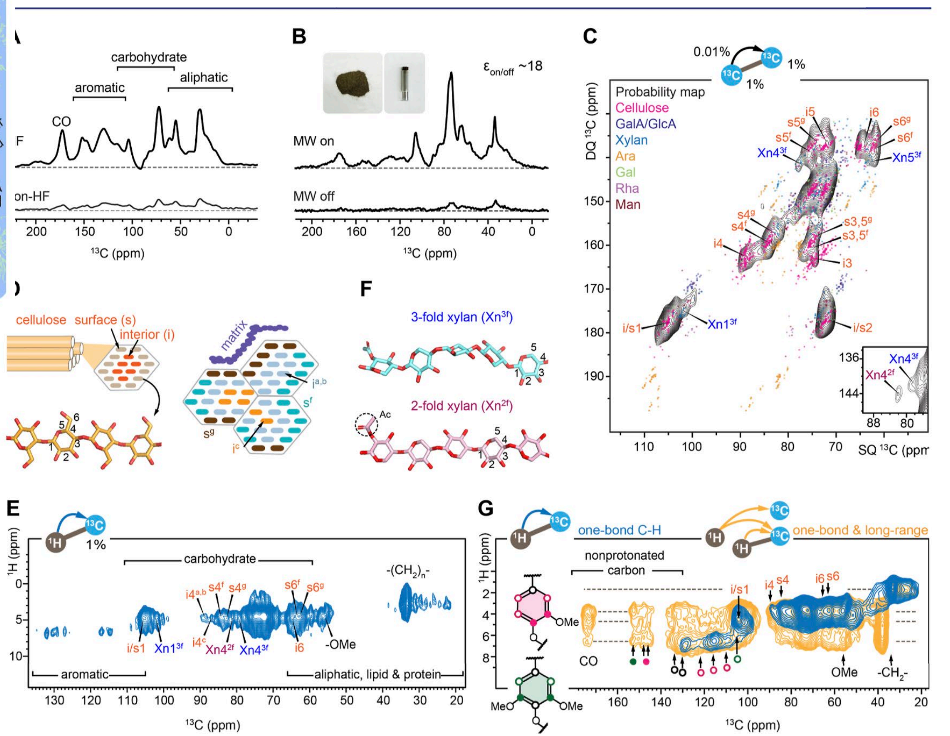


Modern applications

- Modern and real samples ^{13}C-^{13}C
  - Tuo Wang (LSU then MSU)
  - Lots of applications on carbohydrates
  - Cell-wall, wood/rice/bamboo, soil

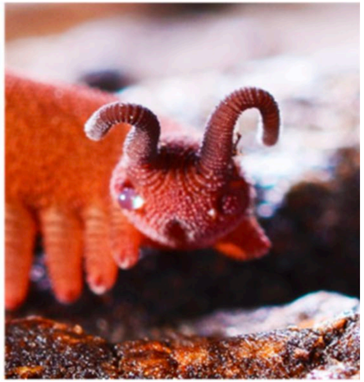


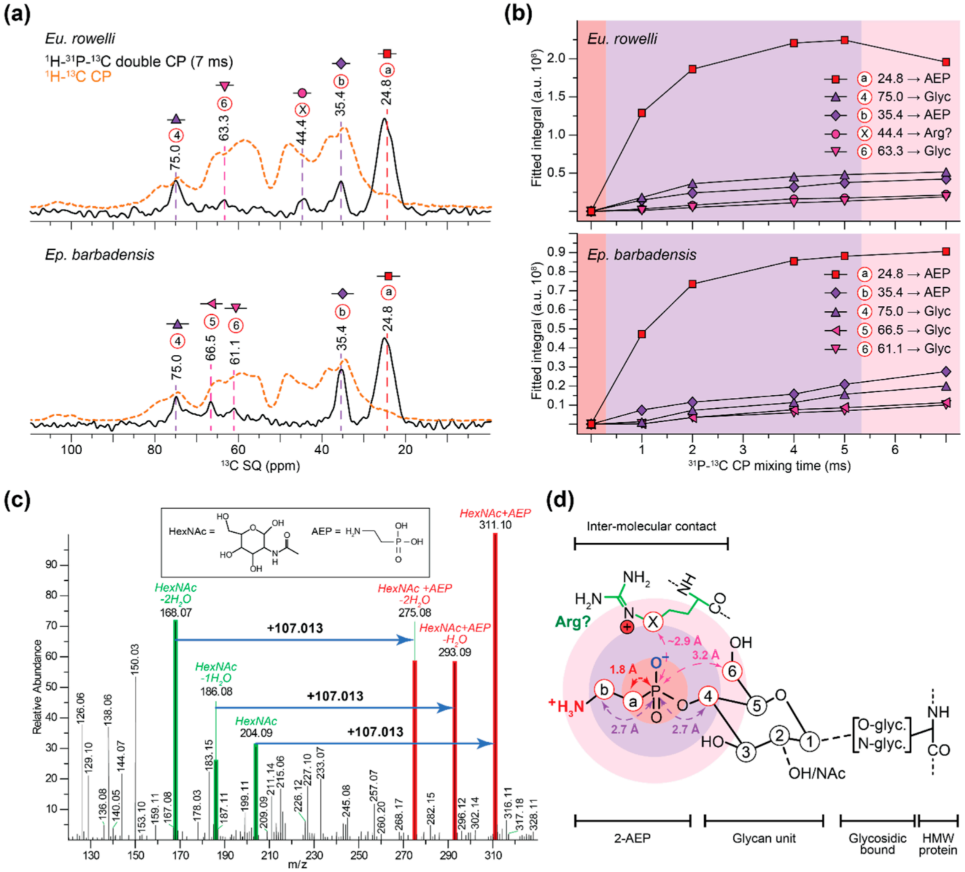
W. Zhao, E. C. Thomas, D. Debnath, F. J. Scott, F. Mentink-Vigier, J. R. White, R. L. Cook and T. Wang, J. Am. Chem. Soc., 2025, 147, 519–531.



Relatively hard

- ^{13}C-^{31}P correlation at NA
  - Detection of phosphonate in velvet worm slime
  - Regular double CP
  - AsymPol-POK (in glycerol/water)





A. Poulhazan, A. Baer, G. Daliaho, F. Mentink-Vigier, A. A. Arnold, D. C. Browne, L. Hering, S. Archer-Hartmann, L. E. Pepi, P. Azadi, S. Schmidt, G. Mayer, I. Marcotte and M. J. Harrington, J. Am. Chem. Soc., 2023, 145, 20749–20754.

Very challenging examples

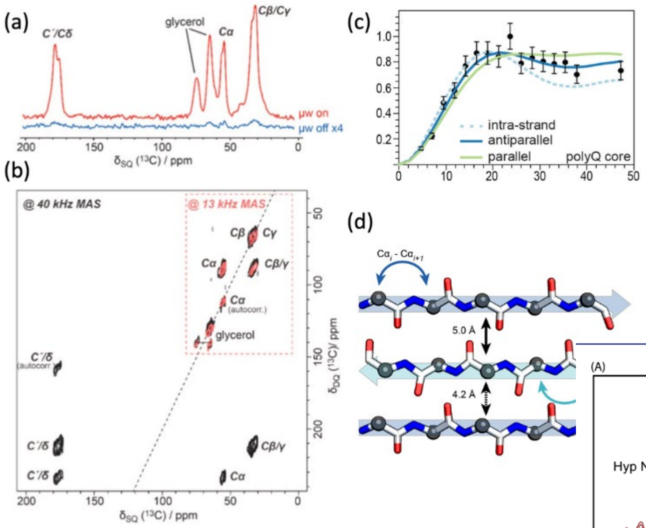
- Natural abundance ^{13}C-^{15}N

A. N. Smith, K. Märker, T. Piretra, J. C. Boatz, I. Matlahov, R. Kodali, S. Hediger, P. C. A. van der Wel and G. De Paëpe, J. Am. Chem. Soc., 2018, 140, 14576–14580.

Aim: collect Natural Abundance ^{13}C-^{15}N correlation
For polyQ

Challenge: run NA ^{13}C-^{15}N TEDOR

Sample: PolyQ
Radical = AMUPol, sedimented

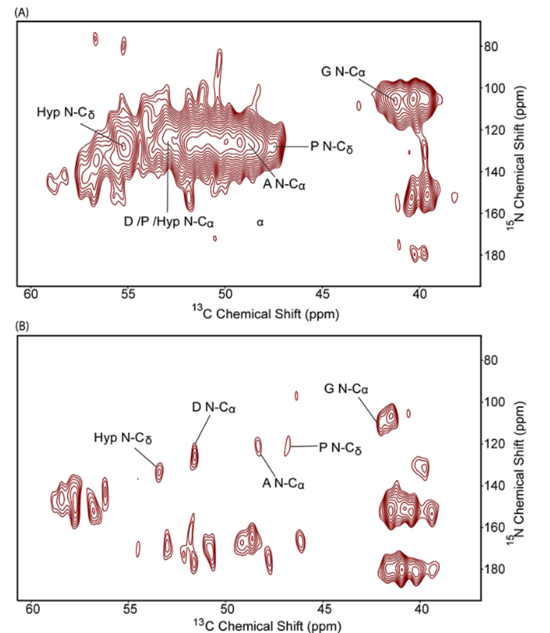


N. Dwivedi, B. Patra, F. Mentink-Vigier, S. Wi and N. Sinha, J. Am. Chem. Soc., 2024, 146, 23663–23668.

Aim: collect Natural Abundance ^{13}C-^{15}N correlation

Challenge: run NA ^{13}C-^{15}N TEDOR

Sample: Bone and cartilages
Radical = AsymPol-POK, water



Other Material Applications

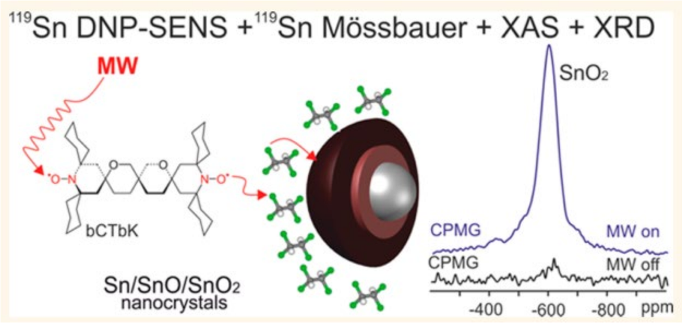
- Tin

Protesescu, L.; Rossini, A. J.; Kriegner, D.; Valla, M.; de Kergommeaux, A.; Walter, M.; Kravchyk, K. V.; Nachtegaal, M.; Stangl, J.; Malaman, B.; Reiss, P.; Lesage, A.; Emsley, L.; Copéret, C.; Kovalenko, M. V. ACS Nano 2014, 8, 2639.

Aim: study Ligand-Capped Sn/SnO_x Nanoparticles

Challenge: detect ^{119}Sn surface signals

Sample:Ligand-Capped Sn/SnO_x Nanoparticles
Radical = bCTbK – Solvent = TCE



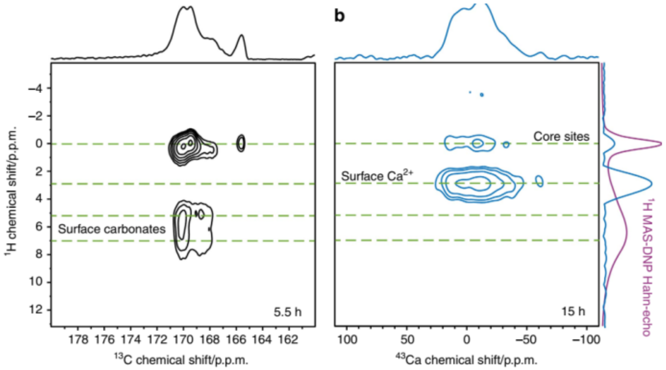
- ^{43}Ca

Lee, D.; Leroy, C.; Crevant, C.; Bonhomme-Coury, L.; Babonneau, F.; Laurencin, D.; Bonhomme, C.; De Paëpe, G. Nat. Commun. 2017, 8, 14104.

Aim: study nano-crystalline apatites

Challenge: detect ^{43}Ca at natural abundance and distinguish core from surface Ca

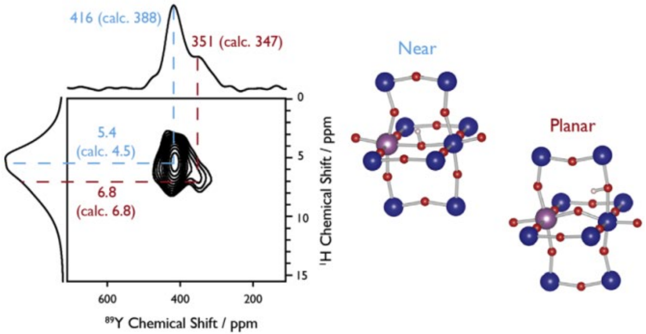
Sample: Carbonated hydroxyapatites
Radical = AMUPol – Solvent = d8-Glycerol/D_2O/H_2O



Other Material Applications

- ^{89}Y

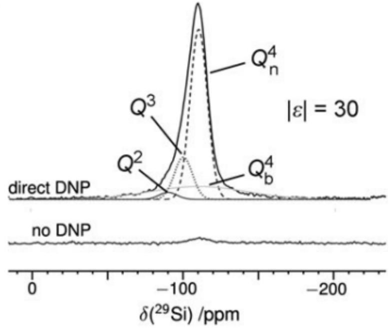
Blanc, F.; Sperrin, L.; Lee, D.; Dervişoğlu, R.; Yamazaki, Y.; Haile, S. M.; De Paëpe, G.; Grey, C. P. J. Phys. Chem. Lett. 2014, 5 (14), 2431–2436.

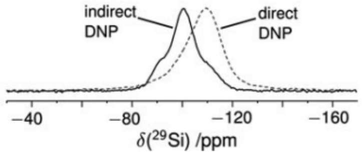


- Direct detection of ^{29}Si

(1) Lafon, O.; Rosay, M.; Aussenac, F.; Lu, X.; Trébosc, J.; Cristini, O.; Kinowski, C.; Touati, N.; Vezin, H.; Amoureux, J. P. Angew. Chemie - Int. Ed. 2011, 50, 8367.

(2) Akbey, U.; Altin, B.; Linden, A.; Özçelik, S.; Gradzielski, M.; Oschkinat, H. Phys. Chem. Chem. Phys. 2013, 15 (47), 20706–20716.





Other Material Applications

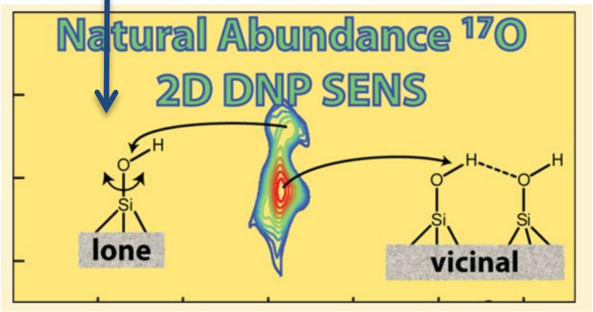
- ^{17}O Particularly difficult isotope:
  - Low natural abundance 0.038%
  - Often large quadrupolar interaction…
  - $^{1}H \rightarrow ^{17}O$ can be very tricky

(1) Blanc, F.; Sperrin, L.; Jefferson, D. A.; Pawsey, S.; Rosay, M.; Grey, C. P. *J. Am. Chem. Soc.* **2013**, *135*, 2975.
(2) Perras, F. a.; Kobayashi, T.; Pruski, M. *J. Am. Chem. Soc.* **2015**, 150622115706000.
(3) Perras, F. A.; Chaudhary, U.; Slowing, I. I.; Pruski, M. *J. Phys. Chem. C* **2016**, *120*, 11535.

Aim: study surface structure and

Challenge: detect ^{17}O on surface!

Using PRESTO CP was possible here due to direct H-O bonding



- More and more applications to challenging systems
  - ^{13}C-^{15}N correlations at natural abundance (Märker, K. et al. *Chem. Sci.* **2017**, *8*, 974.)
  - Study of catalyst containing tungstate (Pump, E.et al. *Chem. Sci.* **2016**.)
  - Study of reduced Graphene Oxide (Leskes, M. et al. *J. Phys. Chem. Lett.* **2017**, *8*, 1078.)
  - ^{17}O in CeO_2 (Hope, M. A. et al. *Chem. Commun.* **2017**, *53*, 2142.)

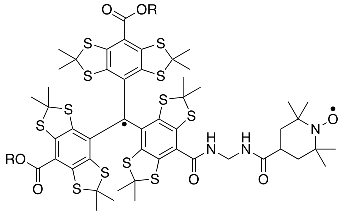
Modern MAS-DNP Challenges

- Solutions?
  - Improve the **hardware**:
    - µw sources (Bruker, CPI, VDI, Bridge12, ETH…)
    - probes (Bruker, PhoenixNMR, Maglab…)
    - close loop Helium cooling and spinning (Osaka/JEOL, CEA Grenoble)
    - pulsed DNP methods (MIT, Konstanz, ENS…)
  - Make better/expand the **polarizing agents**
    - metal centers/intrinsic radicals (Weizmann, Liverpool, Rostock, ISU, EPFL…)
    - different mechanism (AMES, MIT, Northwestern)
    - **improve biradicals (Lyon/EPFL/Marseille, Maglab/CEA/U. Iceland…)**

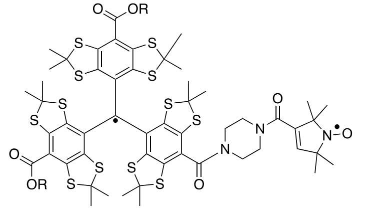
- Which biradical's properties impact most efficiency?
- Sample's properties affect DNP?
- Stereotypical experiments (100 K, modest spinning speed)
- Why some biradicals perform admirably in protonated media?
- Is there an ideal biradical?

- Must be able to make quantitative predictions
- Must obtain physical insights from simulations

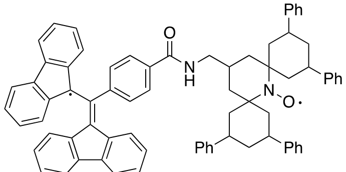
Hetero-biradicals



TEMTriPol-I $D_{a,b}$ ~ 40 MHz, $J_{a,b}$ in [0-200] MHz

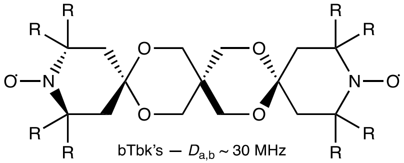


PyrroTriPol-I $D_{a,b}$ ~ 20 MHz, $J_{a,b}$ in [0-20] MHz

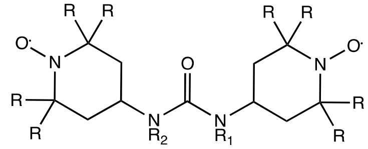


HyTEK2

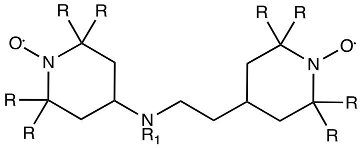
Homo-biradicals



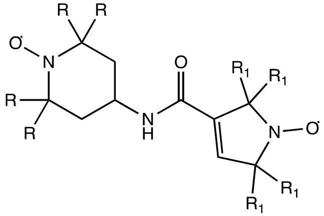
bTbk's — $D_{a,b}$ ~ 30 MHz



bTurea — $D_{a,b}$ ~ 36 MHz $J_{a,b}$ ~ -15 MHz



TinyPol — $D_{a,b}$ ~ 47 MHz $J_{a,b}$ ~ -30 MHz

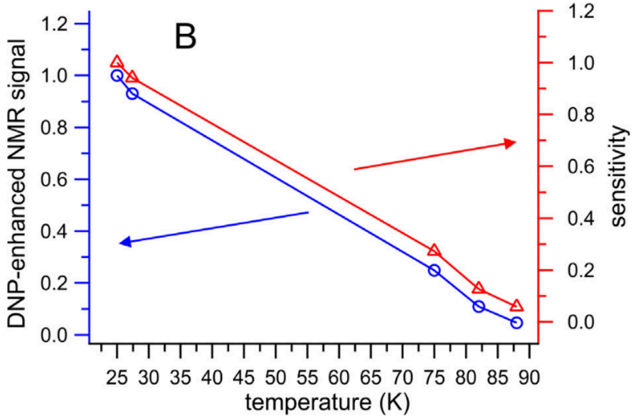


AsymPol— $D_{a,b}$ ~ 56 MHz $J_{a,b}$ ~ 100 MHz

Current state of MAS-DNP

- Three main development
  - Expand the range of temperature of DNP
    - Low T DNP:
      - "Easy" if open loop
      - Complex hardware if close loop
      - Lengthening of the relaxation times: electron and nuclear spins → makes DNP more efficient

- Examples of "open loop"
  - A. Hackmann, H. Seidel, R. D. Kendrick, P. C. Myhre and C. S. Yannoni, *Journal of Magnetic Resonance (1969)*, 1988, **79**, 148–153. → first example but huge LHe consumption
  - K. Thurber and R. Tycko, *Journal of Magnetic Resonance*, 2016, **264**, 99–106. →modern approach, much better ~ 1.5 L of Lhe/h



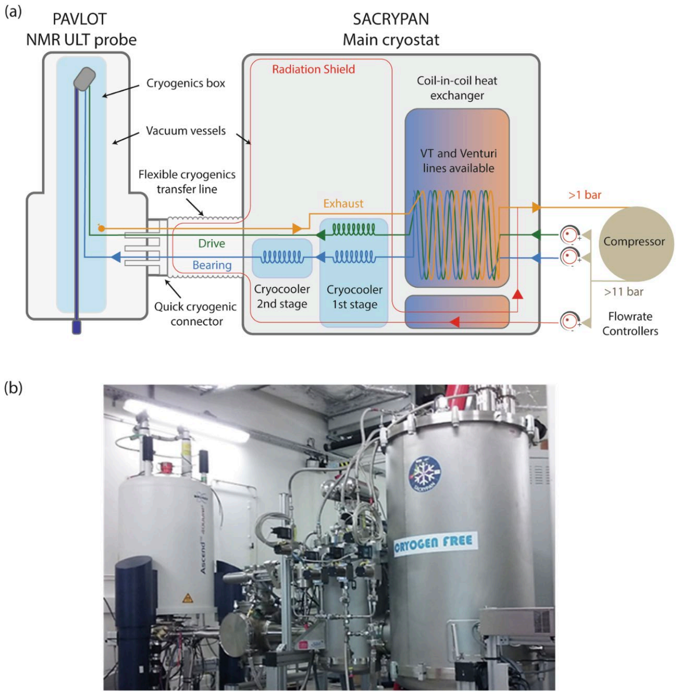
- ~10 SNR gain
- Possible to use low power mw sources (balances cost)
- Expensive in the long term, recycling can be difficult.

→ Closed loop

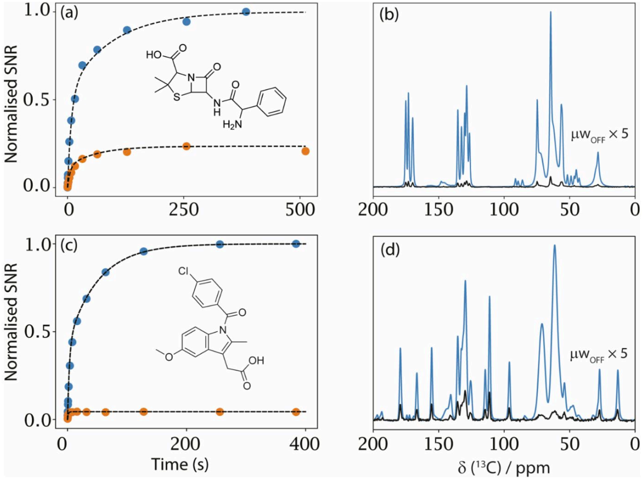
The current state of MAS-DNP

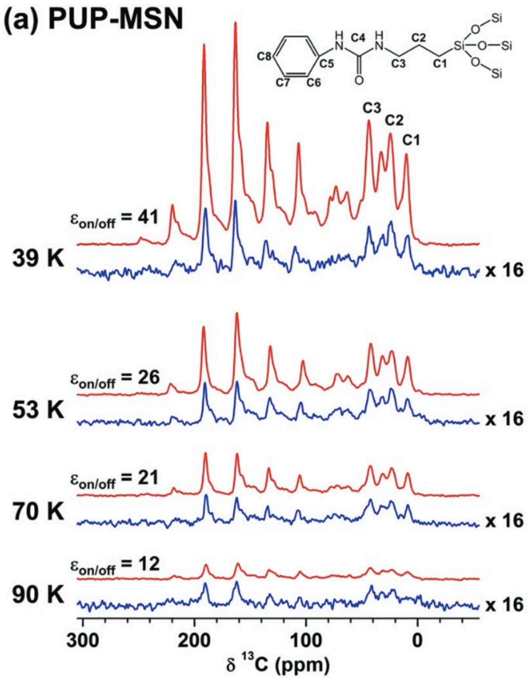
- Three main development
  - Expand the range of temperature of DNP
    - Close loop examples
      - Two groups, De Paëpe (France) and Matsuki (Japan)
      - Complex and expensive, but incredibly efficient

Y. Matsuki, T. Kobayashi, J. Fukazawa, F. A. Perras, M. Pruski and T. Fujiwara, Phys. Chem. Chem. Phys., 2021, 23, 4919–4926.



S. Paul, E. Bouleau, Q. Reynard-Feytis, J.-P. Arnaud, F. Bancel, B. Rollet, P. Dalban-Moreynas, C. Reiter, A. Purea, F. Engelke, S. Hediger and G. De Paëpe,, Journal of Magnetic Resonance, 2023, 356, 107561.

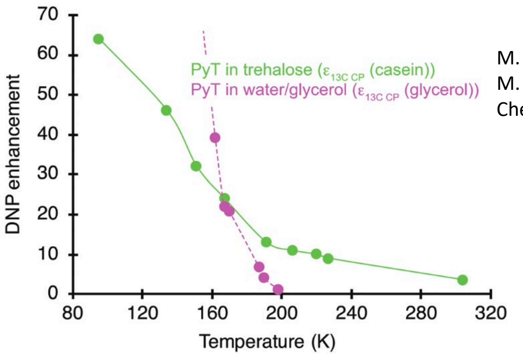




The current state of MAS-DNP

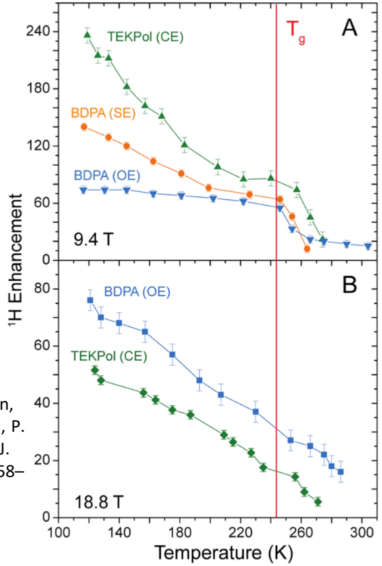
Spinning speed is limited by speed of sound of the gas

- Three main development
  - Expand the range of temperature of DNP
    - Do higher temperature DNP: why?
      - Access dynamics
      - Spin sample faster, closer to RT capabilities
    - Who:
      - H. Oschkinat – U. Akbey (first DNP T = 200 K)
      - Lyon/EPFL/Florence/Marseille: Lesage/Emley/Lelli/Ouari
      - Maglab (Faith and I)
    - How:
      - Use glass matrices with high T_g
      - E.g. Ortho-Terphenyl, Trehalose, or Sorbitol



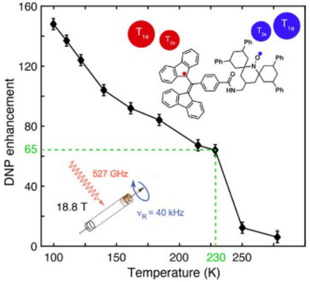
M. Kaushik, H. Lingua, G. Stevanato, M. Elokova, M. Lelli, A. Lesage and O. Ouari, NMR, Phys. Chem. Chem. Phys., 2022, 24, 12167–12175.

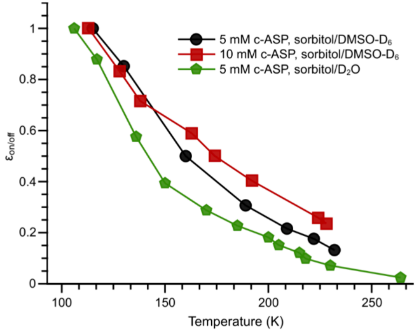
F. J. Scott, S. Eddy, T. Gullion and F. Mentink-Vigier, J. Phys. Chem. Lett., 2024, 8743–8751.

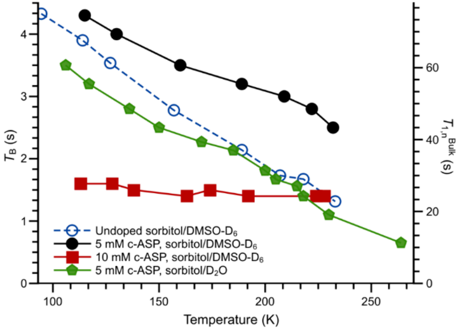


M. Lelli, S. R. Chaudhari, D. Gajan, G. Casano, A. J. Rossini, O. Ouari, P. Tordo, A. Lesage and L. Emsley, J. Am. Chem. Soc., 2015, 137, 14558–14561.

G. Menzildjian, A. Lund, M. Yulikov, D. Gajan, L. Niccoli, G. Karthikeyan, G. Casano, G. Jeschke, O. Ouari, M. Lelli and A. Lesage,, J. Phys. Chem. B, 2021, 125, 13329–13338.



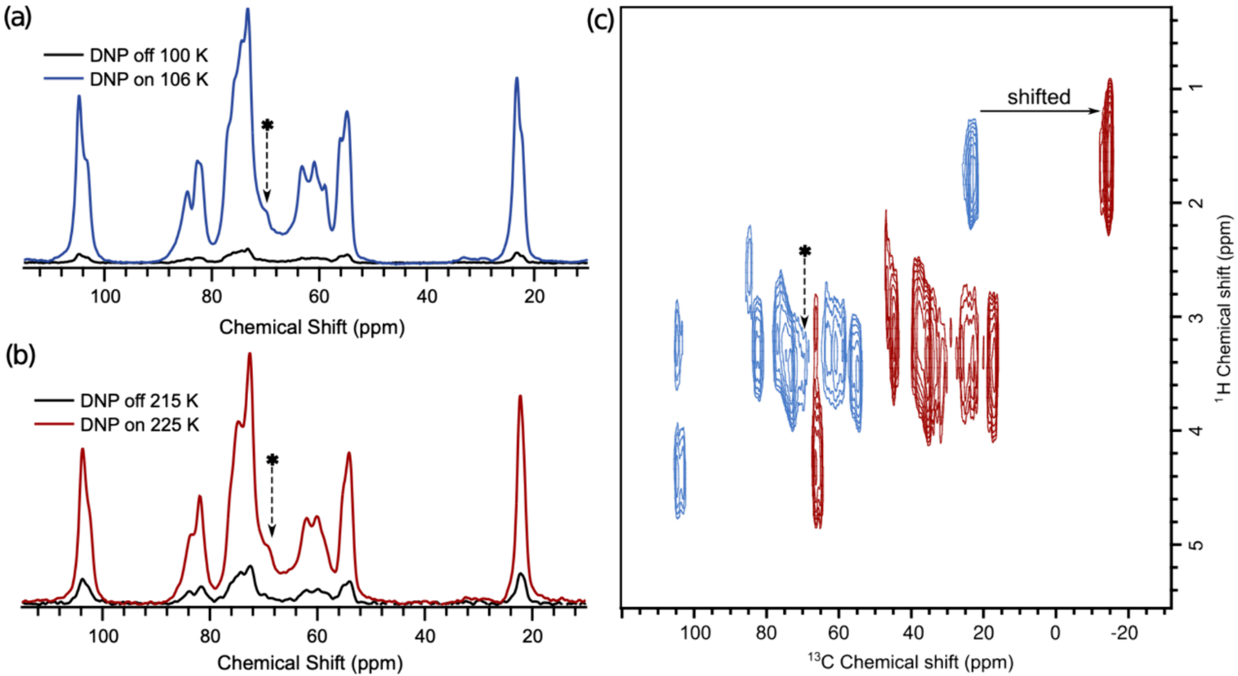




The current state of MAS-DNP

- Three main developments
  - Expand the range of temperature of DNP
    - Do higher temperature DNP: why?
      - Access dynamics
      - Spin sample faster, closer to RT capabilities
    - Who:
      - H. Oschkinat – U. Akbey (first DNP T = 200 K)
      - Lyon/EPFL/Florence/Marseille: Lesage/Emley/Lelli,
      - Maglab (Faith and I)
    - How:
      - Use glass matrices with high T_g
      - E.g. Ortho-Terphenyl, Trehalose, or Sorbitol
      - **We used sorbitol because it has small spectrum overlap**

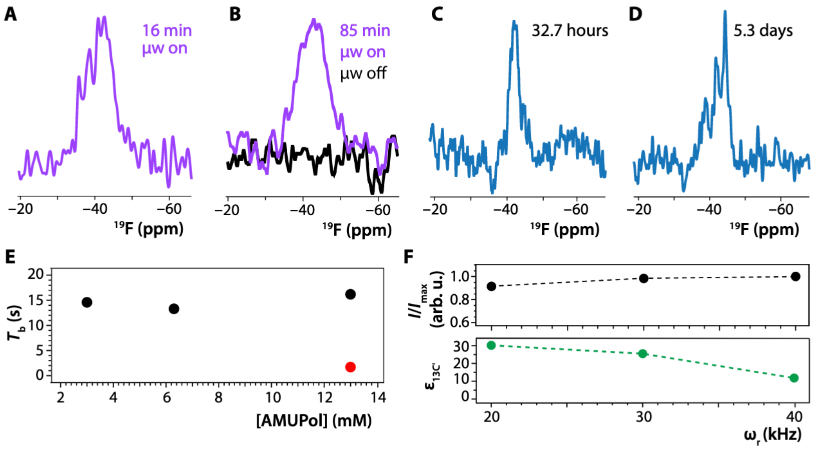
F. J. Scott, S. Eddy, T. Gullion and F. Mentink-Vigier, Sorbitol-Based Glass Matrices Enable Dynamic Nuclear Polarization beyond 200 K, J. Phys. Chem. Lett., 2024, 8743–8751.



The current state of MAS-DNP

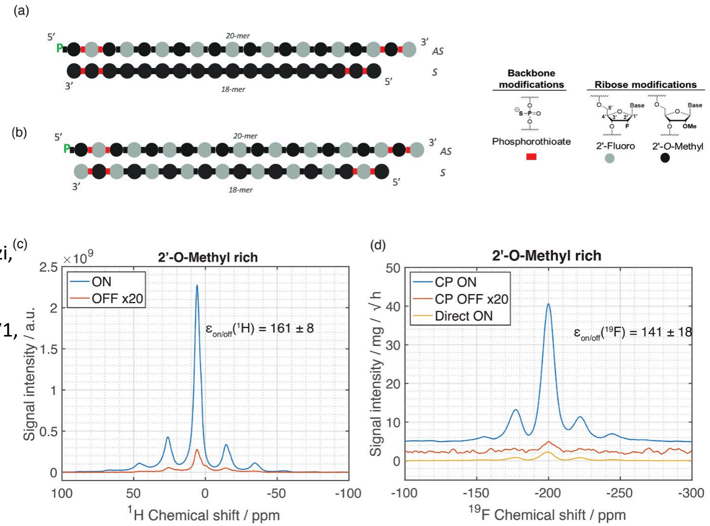
- Three main developments
  - Expand the range of temperature of DNP
    - Low temperature
    - High temperature
  - Access new isotopes → probe development
    - Bruker leads the way
    - NHMFL is funded for this
    - JEOL may be working on it
    - CEA Grenoble → for very low temp
      - ^{19}F
      - Very low gamma (e.g. ^{33}S)
  - Develop new protocols
    - Sample preparation
    - New biradicals
    - New mechanisms

K. T. Movellan, W. Zhu, D. Banks, J. Kempf, B. Runge, A. M. Gronenborn and T. Polenova, Science Advances, 2024, 10, eadq3115.



Direct ^{19}F DNP

M. Šoltésová, A. C. Pinon, F. Aussenac, J. Schlagnitweit, C. Reiter, A. Purea, R. Melzi, F. Engelke, D. Martin, S. Krambeck, A. Biscans, E. Kay, L. Emsley and S. Schantz,, Journal of Magnetic Resonance, 2025, 371, 107827.



^1H → ^{19}F DNP
(likely the future)

Conclusion

- DNP
  - Almost as old and EPR and NMR
  - DNP is the brain child of both methods
  - Mostly applied to particle physics first, only to chemistry starting in 1985.

- Promising techniques
  - Combined with MAS and high field → 1993, Griffin – Temkin
  - First commercial setup in 2009 (400 MHz, 9.4 T)
  - MAS-DNP has allowed detection of surface properties with a very high sensitivity
  - Polarize protons, do CP to target nucleus
  - Broad range of applications:
    - Mesoporous Materials
    - MOF's
    - Nano/MesoCrystal

  - Used to enhance commonly studied isotopes
    - C, N, O, Si, Al
  - And more difficult ones Sn, Y, Ca…
  - Natural abundance is possible!

- Challenges
  - Sample preparation may be challenging.
    - Moderate thinking about it

  - Initial tests are easy
    - Further improvement needs some work

Conclusions

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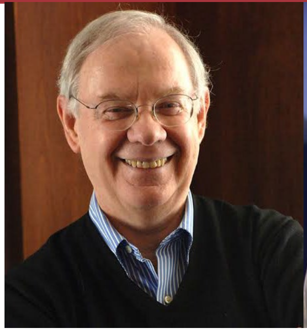
- Promising techniques
  - Combined with MAS and high field → 1993, Griffin – Temkin
  - First commercial setup in 2009 (400 MHz, 9.4 T),
    significant role by Melanie Rosay, Bruker, in collaboration with R.G. Griffin


R.G. Griffin


M. Rosay

Funding

- This workshop has received funding from:
  - The European Union’s Horizon 2020 research and innovation programme under Grant Agreement No 101008500
  - The National Resource for Advanced NMR Technology, which is funded by NIH RM1-GM148766.
  - The National High Magnetic Field Laboratory (NHMFL), which is funded by the National Science Foundation Cooperative Agreement (DMR-2128556) and by the State of Florida.
  - Bruker Biospin