Dynamic nuclear polarisation: from polarised targets to medical imaging

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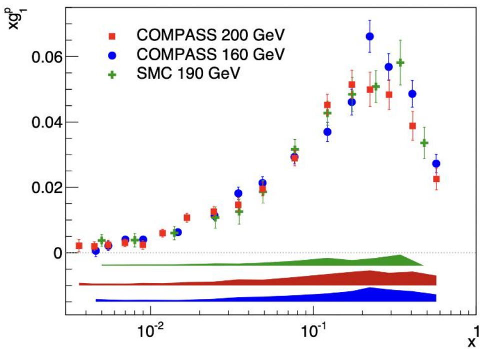
Outline

- Brief history of Polarised targets – CERN-centric
- NMR and MRI
- Basic principles of DNP
- Radiation-detected NMR
- Current DNP project at CERN

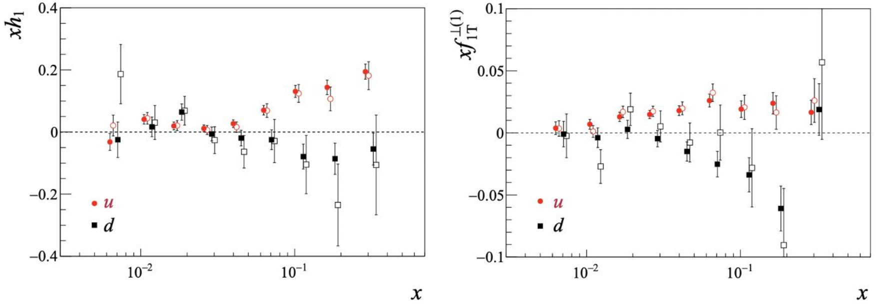
Polarised targets – a bit of history

- A. Abragam 1960s, M. Borghini, T. Niinikoski 1970s at CERN
- Long history of CERN experiments – EMC, SMC, COMPASS
- Measurements of (SI)DIS with muon beams and L or T polarized target
- Nucleon spin structure – Spin crisis 1988
- Transverse structure of the nucleon – TMD PDFs



$\Delta\Sigma$~0.3

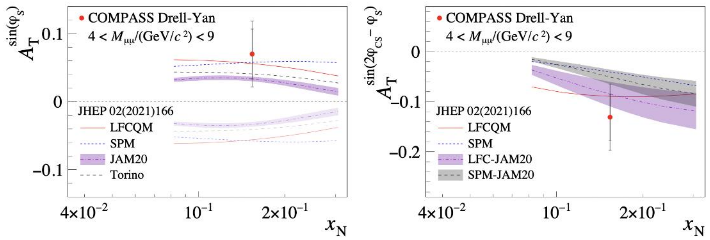
PLB 753 (2016) 18



Accepted in PRL, hep-ex/2401.00309
See talk by B. Parsamyan in QCD session

Polarised targets – a bit of history

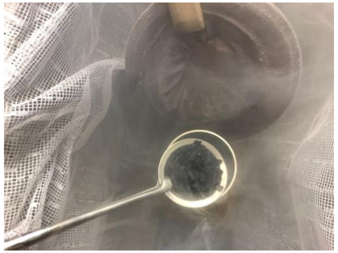
- Common materials – NH_3 and ^6LiD – good radiation hardness
- Recently polarised Drell-Yan measurements – test of Sivers function sign change
- More challenging – higher heat load and possible radiation damage



Accepted in PRL, hep-ex/2312.17379,
See talk by M. Niemiec in QCD session

See recent paper on ammonia behaviour in 190 GeV hadron beam
NIMA 1025 (2022) 166069

NH_3



^6LiD

NMR and MRI

- Response of nuclear spins in static magnetic field to RF excitation
- $P_{nuclear}$~10^{-5} at RT and ~ a few T magnetic field
- Low sensitivity as Signal $\propto$ P $\propto B_{ext}$, where $P = \tanh\left(\frac{\mu B}{kT}\right)$
- Currently 1.2GHz (~28 T) spectrometer available on the market
- MRI machines: 1.5 T, 3 T (becoming mainstream), 7 T, 11.7 T (experimental)
- Increasing polarisation via hyper-polarisation techniques

1.2 GHz NMR

11.7 T MRI

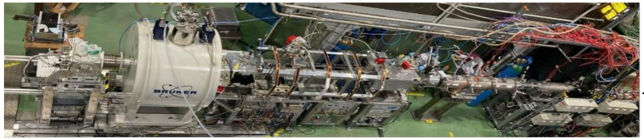
Big and expensive

Polarisation methods

Spin exchange optical pumping (SEOP)

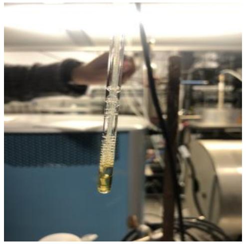
Dynamic nuclear polarisation (DNP)

Optical pumping (OP)



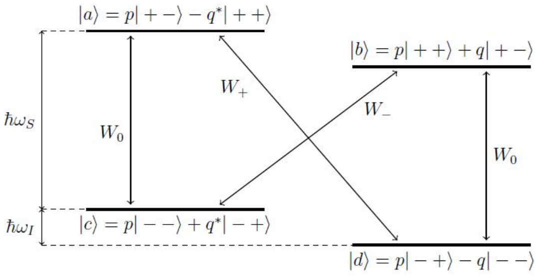
Nuclear Polarisation

Signal amplification by reversible exchange (SABRE)

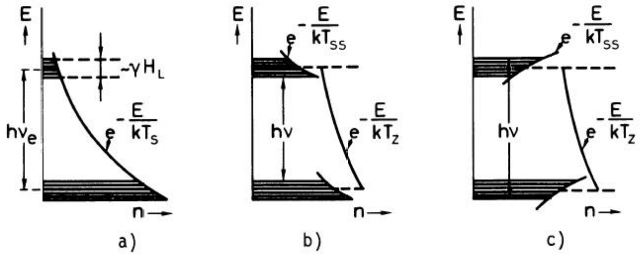


Principles of DNP

- Low temperature, high magnetic field: 1K, 2.5 T
- Equilibrium polarization low for nuclei: 0.25 % for protons
- Very high electron polarisation: >99 %
- RF induced spins flips between unpaired electron and nuclei
- Unpaired electrons – radicals – chemical or radiation induced

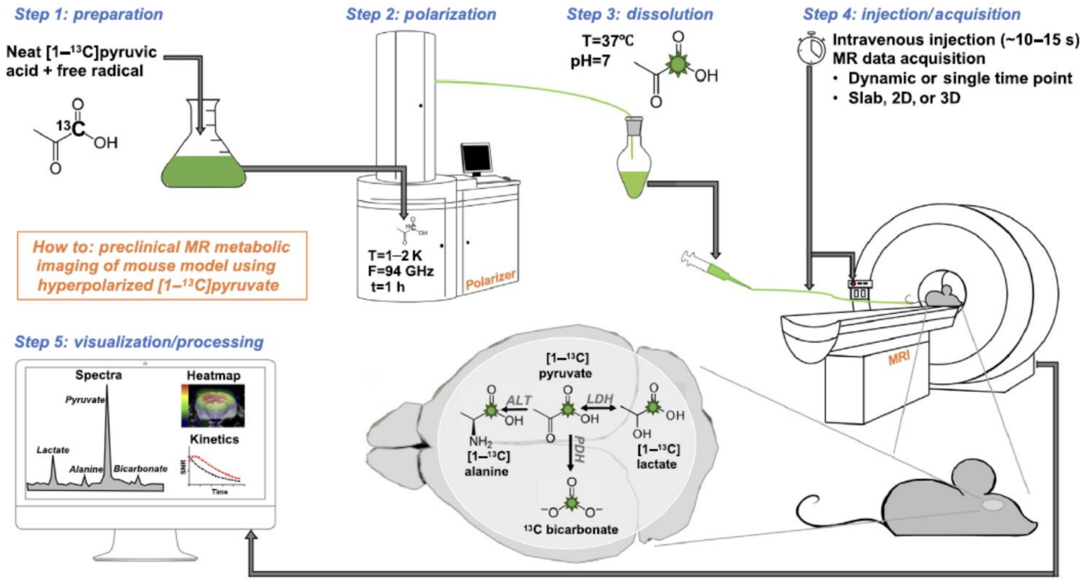


2 theoretical descriptions



Dissolution DNP

- Frozen sample at 1K
- Does it have a practical use?
- Yes! - the sample can be rapidly dissolved and transferred



Le Page L. M. et al., Trends in Neurosciences 43 (2020)

NMR without magnet – ZULF NMR

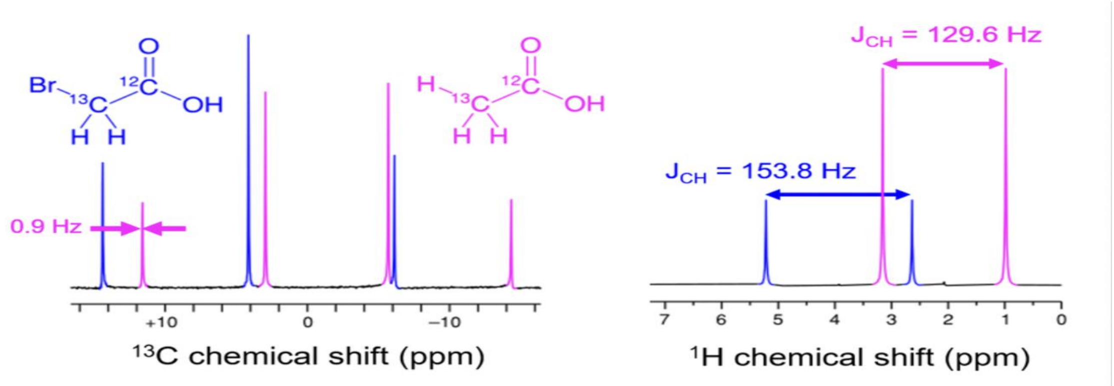
- Conventional NMR:

  polarisation of nuclei by external field

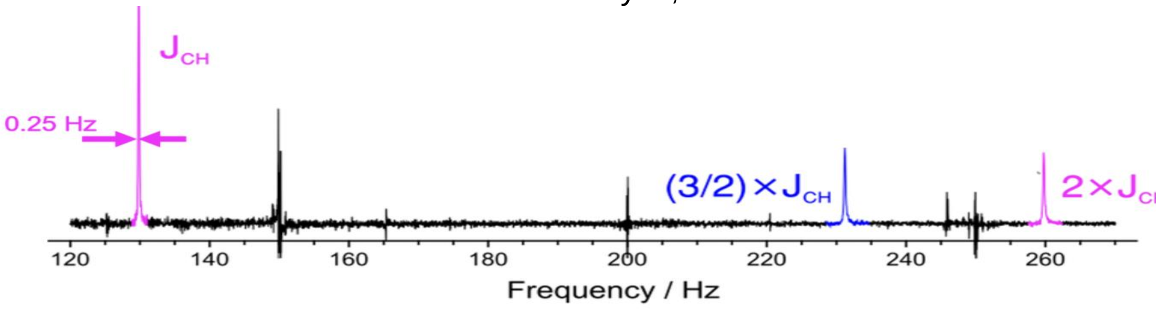
  $H_{Zeeman} >> H_{spin\text{-}spin}$

- ZULF: $H_{Zeeman} << H_{spin\text{-}spin}$
- Need to provide polarised sample
- No more chemical shift, but scalar-couplings dominate
- Advantages:
- No need for large magnet → small setup
- Low resonance frequency
- Can measure on metal samples

1.5 T



From M. Tayler, wiki

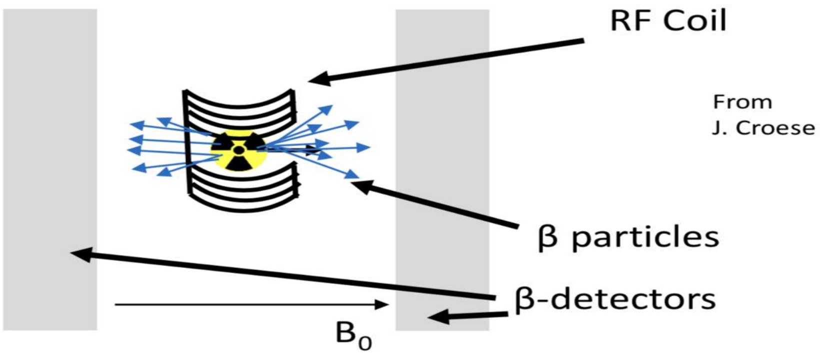


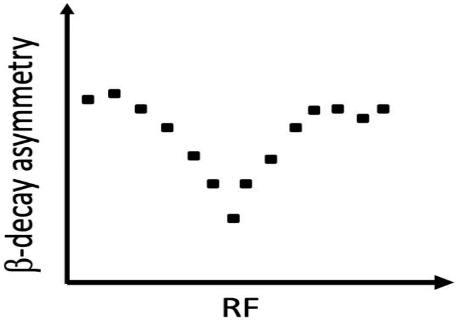
1 nT

RD-NMR

- Use of anisotropic β-decay or γ-decay
- Spin >1/2 for β-decay or spin >1 for γ-decay
- RF-excitation to "destroy" the asymmetry
- Example: Measure β-decay asymmetry

$$W(\theta) = 1 + a\frac{v}{c}P_I \cos\theta$$

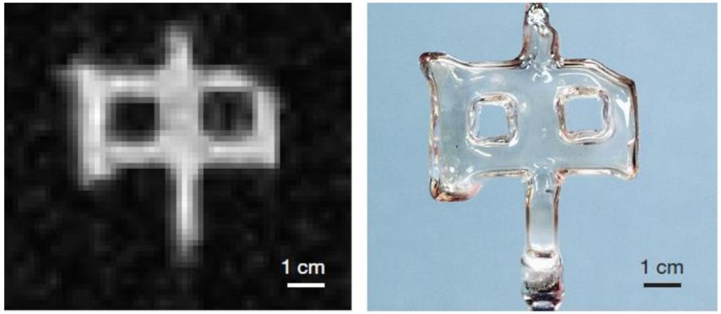




- Needs initial polarisation above thermal equilibrium
- Enhanced sensitivity wrt conventional NMR $>10^6$

RD-NMR and γ-MRI

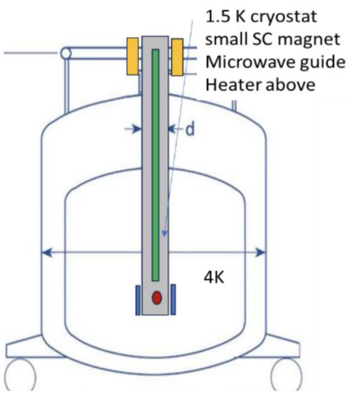
- Combination of PET/SPECT sensitivity and MRI space resolution
- Long-lived Xe isotopes: ^{129m}Xe, ^{131m}Xe, ^{133m}Xe, $t_{1/2}$~days
- Proof of principle: Y. Zheng et al., Nature 537, 652 (2016)



- Currently: EU funded Emerging technologies project
- Using Spin-exchange optical pumping for nuclear polarisation
- DNP can be used to polarise radioactive Xe

DNP project at CERN

- Idea to build compact and affordable setup fitting standard lHe dewar
- Polarise both stable and (for the first time ever) radioactive nuclei using DNP
- In-house know-how – SC magnets, NMR, cryogenics
- First radioactive isotope – ^{18}F, $t_{1/2}$ =110 min, produced for PET
- Can help not only conventional NMR but also to spread use of RD NMR
- Supported by CERN Medical applications funding
- RD-NMR workshop at CERN August 2024



Summary and Outlook

- DNP allowed to greatly improve our knowledge of nucleon spin structure
- NMR/MRI suffer from low sensitivity
- DNP can enhance the sensitivity while keeping cost and size down
- DNP could allow for wider spread of RD-NMR technique
- Currently CERN-MA funding supports a development of compact and affordable system for DNP to be used for both stable and radioactive nuclei

Thank you for your attention!

- Our team and collaborators :
- CERN: MP, N. Azaryan, M. Kowalska, A. Sparks, N. Doshita, T. Koettig, A. Dudarev
- Ruhr Universitat Bochum: W. Meyer, G. Reicherz
- HUG: A. Grotzky, V. Bonvin, V. Garibotto

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