Novel ^{129}Xe SEOP polarizer for medical and material studies

Anna Wojna-Pelczar

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Motivation

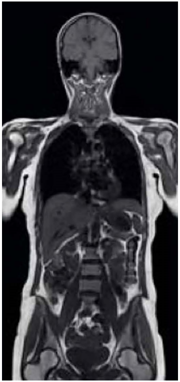
- Lungs - challenging to diagnose e.g. ^{1}H MRI
- SPECT, PET, MDCT, spirometry brought exploitable parameters, but...
- NMR signal is proportional to polarization and density

$$S \sim \rho \cdot P, P = \frac{N_{\downarrow} - N_{\uparrow}}{N_{\downarrow} + N_{\uparrow}}$$

- ^{1}H MRI:

$$P \sim \frac{\gamma \hbar B_0}{2 k_B T}, T = 296K, B_0 = 1.5T, P \sim 10^{-5}\%$$

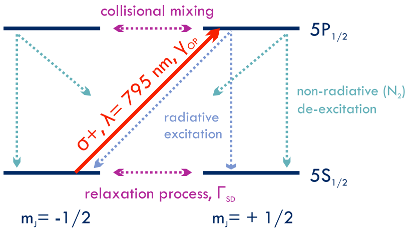
- High-resolution morphology, non-invasive/non-ionizing imaging (MRI)
- ^{3}He and ^{129}Xe: in order to keep 1 atm. $\rightarrow$ boost P with MEOP and SEOP, P $\rightarrow$ 1 - 80%

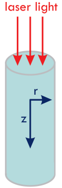


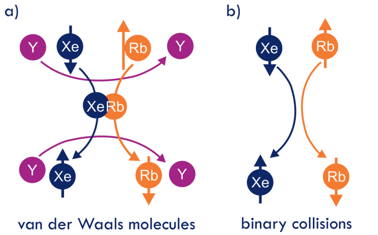
Principles - ^{129}Xe vs. ^{3}He

Isotope	^{129}Xe	^{3}He
Nuclear spin	1/2	1/2
Abundance [%]	26.4	1.3×10^{-4}
Gyromagnetic ratio [MHz/T]	11.778	32.433
Chemical shift [ppm]	7500, 200 ppm in lungs	0.8
Characteristics	anestetic, lipofilic	neutral
	neutral	

Principles - Spin Exchange Optical Pumping







- Optical pumping (Kastler, 1950)
- Magn. field: B_0, buffer gases: N_2, ^4He
- 795 nm, $\sigma\pm$, high power

$$P_{Rb}(z,r) = \frac{\gamma_{OP}(z,r)}{\gamma_{OP}(z,r) + \Gamma_{SD}}$$

$$P_{Xe} = \langle P_{Rb} \rangle \frac{\gamma_{SE}}{\gamma_{SE} + \Gamma}(1 - e^{-(\gamma_{SE}+\Gamma)t})$$

$$\Gamma_{SD} = \sum_i k^i_{SD}[M_i]$$

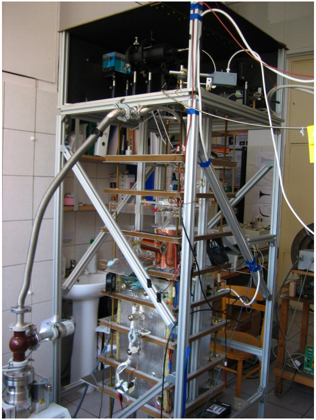
$$k^{Xe}_{SD} = 5200 \times 10^{-18} cm^3 s^{-1}!!!$$

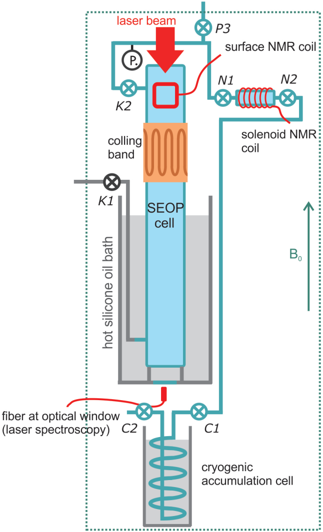
$$\gamma_{SE} \sim \quad vdW + b.c.$$

^{129}Xe polarizer - Objectives

- ^{129}Xe (enriched > 0.91), N_2, ^{4}He mixes with Rb vapour
- low ^{129}Xe content
- moderate pressure regime $\sim$ 1 bar
- large the SEOP cell: 80 cm, 10 cm diameter, 5 L
- high power laser source 60 Watts
- homogeneous magnetic field
- cryogenic accumulation
- polarization readout system: NMR

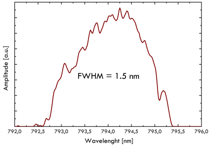
^{129}Xe polarizer



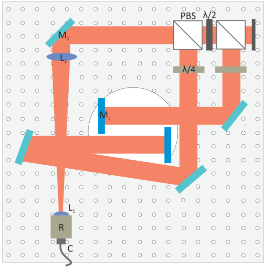


^{129}Xe polarizer - Optics

- Scientific DUO FAP System, *Coherent*, 2×30 Watt diodes, linewidth < 2 nm,

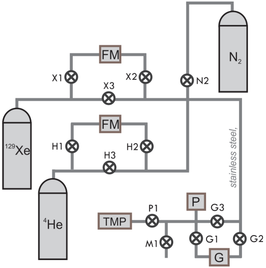


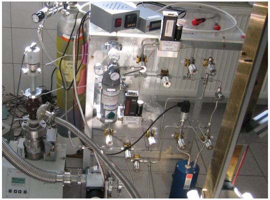
- two bundle fiber (2 × 800 μm) → radiator for colimator
- a home-made beam expander
- 2 × 2 $\sigma \pm$ (2 cm diam.) beams on optical window
- 45 Watts inside the SEOP cell



^{129}Xe polarizer - Gas distribudion and Rb vapour

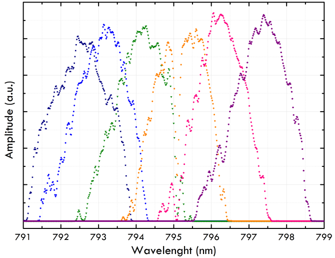
- Rb: easy to vaporize, good availability of relatively cheap, high-quality, high-power laser sources at D_1 line
- differnet content - separate distribution
- gases mix inside the SEOP cell

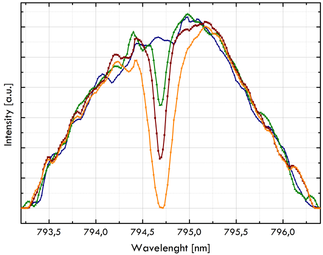




Initial results - laser tuning and spectrum profile

- The profiles were collected from laser beam passing through the SEOP cell
- The adapted Carl Zaiss Jena spectrometer (calibrated with a reference lines D_1 and D_2 from a small rubidium cell with radio frequency discharge)
- The spectral resolution of this unit is about 0.02 nm
- **New laser source is being built**





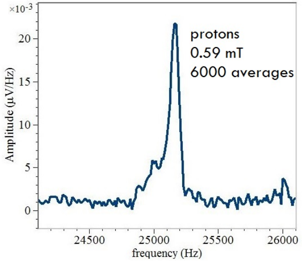
N_2 212 mbar (blue), N_2 248.2 (green),
N_2 and ^{4}He 314.0 mbar (red),
N_2 and ^{4}He 414.0 mbar (orange)

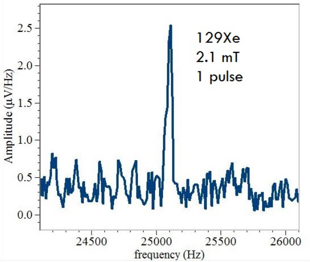
Initial results - ^{129}Xe NMR signal and its calibration

- RF coil (6 cm $\times$ 6 cm)
- HP ^{129}Xe NMR signal from the SEOP cell containing 5.7% ^{129}Xe, 20% N_2 and 74.3% ^{4}He acquired at 2.1 mT
- water NMR spectrum at 0.59 mT, 6000 averages
- Max. polarization after t$\sim$ 30 min

$$P_{Xe} = \frac{S_{Xe} P_H N_H \gamma_H sin(\alpha_H) f(\nu_H) e^{-\frac{t_{dH}}{T_{2H}}}}{S_H N_{Xe} \beta_{Xe} \gamma_{Xe} sin(\alpha_{Xe}) f(\nu_{Xe}) e^{-\frac{t_{dXe}}{T_{2Xe}}}}$$

^{129}Xe: N_2 : ^{4}He	P_{Xe}	Perform.
0.020 : 0.200 : 0.780	15%	0.2 L/h
0.057 : 0.20 : 0.743	8%	0.5 L/h

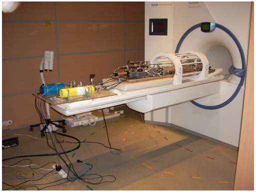




Near future plans

- Laser improvement: 795 nm diode with diffraction grattings
- NMR signal measurement from HP ^{129}Xe in cryogenic accumulation cell

- Human lungs image with HP ^{129}Xe



More motivation - Exploring Lung Function

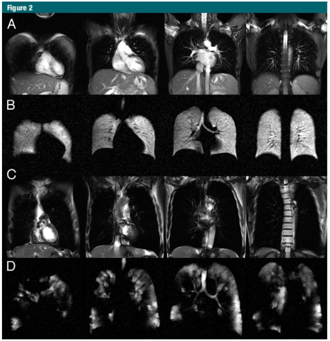
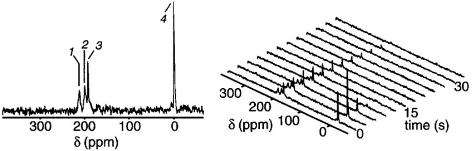


Figure 2: Selected sections from representative ^{129}Xe ventilation and ^{1}H MR anatomic images in individual subjects. *A*, Steady-state free-precession ^{1}H MR images in a healthy volunteer. *B*, Corresponding ^{129}Xe ventilation MR images in the same healthy volunteer. *C*, Steady-state free-precession ^{1}H MR images in a subject with COPD. *D*, Corresponding ^{129}Xe ventilation MR images in the same subject with COPD show substantial ventilation defects and regions lacking ventilation.

Radiology: Vol. 262, No. 1, 2012

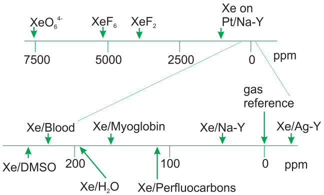


1 - red blood, 2 - lung tissue,
3 - blood plasma adipose tissue,
4 - xenon gas

Concepts in Magnetic Resonance, Vol. 11 (4) 203-223, 1999

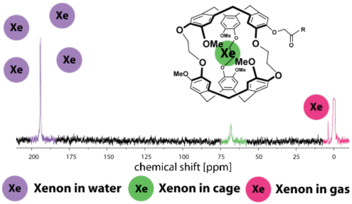
^{129}Xe follows the same pathway as oxygen:
→ from alveolar gas spaces to septal tissue and blood
→ gas exchange parameters (alveolar surface area, septal thickness and vascular transit times).

- ^{129}Xe has large electronic cloud - chemical shift ∼ 7500 ppm



T. Pietra and H.C. Gaede, Adv. Mater 7, 10, 826, 1995

- Encapsulating HP ^{129}Xe in Cryptophane



the Wemmer Lab & A. Pines & M. Francis

Staff:

Dr Tadeusz Pałasz
Anna Wojna-Pelczar (PhD student)

Our website:

chaos.if.uj.edu.pl/~ksenon/

Funds:

National Laboratory for Quantum Technologies

Thank you for your attention!

Chemical shift

On the NMR spectrum scale, the position of resonance is given by δ, where

$$\delta = \frac{\nu - \nu_{TMS}}{\nu_0}$$

$\nu - \nu_{TMS}$ is the frequency difference between the resonance of the signal of interest and the resonance of TMS; ν_{TMS} will always be in units of Hz (from 1 Hz to a few thousand Hz);

ν_0 is the center frequency of the B_1 field in megahertz (MHz). If B_0 = 7.05 T, = 300 MHz for ^{1}H nuclei or 75 MHz for ^{13}C nuclei. If B_0 = 11.75 T, = 500 MHz for ^{1}H nuclei or 125 MHz for ^{13}C nuclei.