Low Field MRI of Laser Polarized Noble Gases

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Outline

- Introduction to conventional MRI
- Low field MRI of Laser Polarized (LP) noble gases
  - Spin Exchange Optical Pumping (SEOP)
  - Nuclear Magnetic Resonance (NMR) signals
  - MRI Gradient Coils
  - Xe-129 gas MRI
  - He-3 gas MRI
- Adapting our apparatus for small animal MRI

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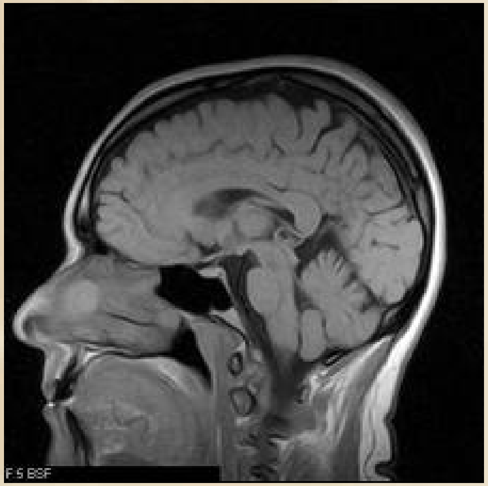
Introduction to MRI

- First paper about Magnetic Resonance Imaging: P. C. Lauterbur, Image Formation by Induced Local Interactions: Examples Employing Nuclear Magnetic Resonance, Nature, 242, 1973
- Since then, MRI has experienced rapid growth and is now the most powerful diagnostic tool.



Pros and Cons of MRI

- Advantages:

1) Safety: Non-invasive, no radiation
2) Flexibility:

   a, Image content is under control

   b, Image of an arbitrary plane can be obtained.

- Disadvantages:

1) Expensive
2) Not for everyone
3) LIMITED FOR LUNG IMAGING

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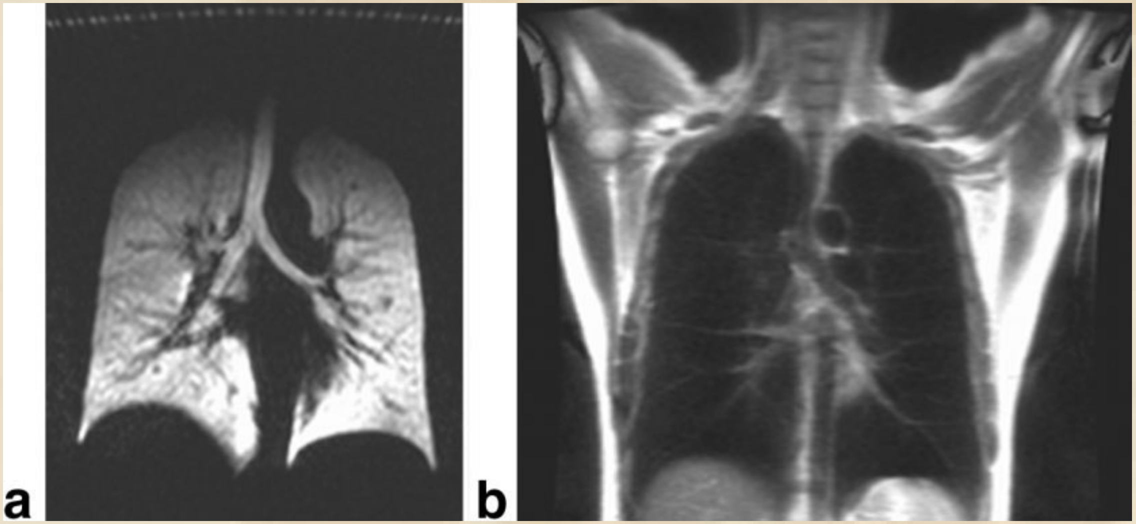
- A new branch for MRI: Laserpolarized (LP) Noble Gas Lung Imaging.
- M.S. Albert, G.D. Cates, et al, Biological magnetic resonance imaging using laser-polarized ^{129}Xe, Nature, 370, 1994



a, 4.5mM of 40% polarized 3He
b, conventional proton MRI of the lung parenchyma

Sean B. Fain, et al. Functional Lung Imaging Using Hyperpolarized Gas MRI

2 Tesla vs 0.002 Tesla

Advantages of performing MRI at a low field:

- More homogeneous holding field
- Compatible with pacemakers and other metal implants
- Much Cheaper

Low field imaging is only possible with LP noble gases.

Polarization of a spin-1/2 system

$$P = \frac{N_+ - N_-}{N_+ + N_-}$$

N_+ and N_- are the number of spins in each of the two possible states.

Thermal Polarization:

$$P = \tanh\left(\frac{\gamma\hbar B}{2kT}\right)$$

At T=300K, the polarization of ^{1}H in 1T field $\sim 3.4\times10^{-6}$.

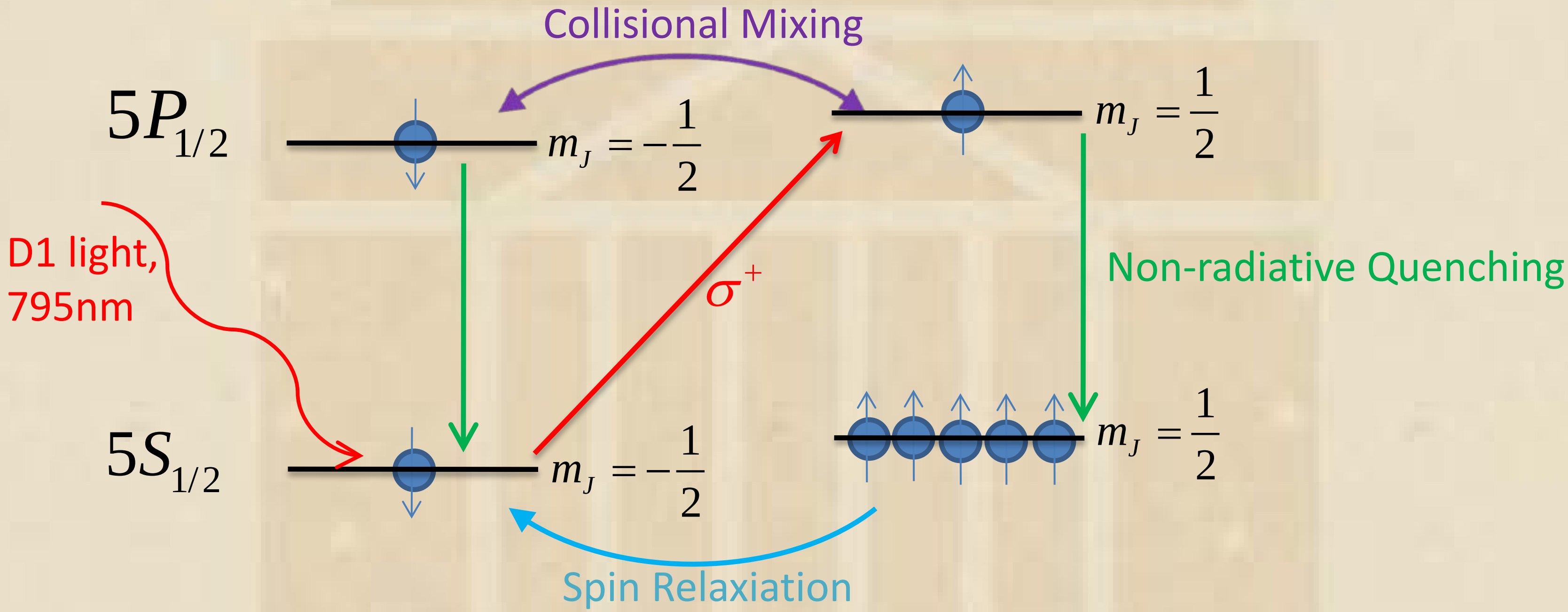
By SEOP, polarization of ^{3}He or ^{129}Xe $\sim$ 50%,

10^5 times higher!

That's why they are also called Hyperpolarized (HP) gases.

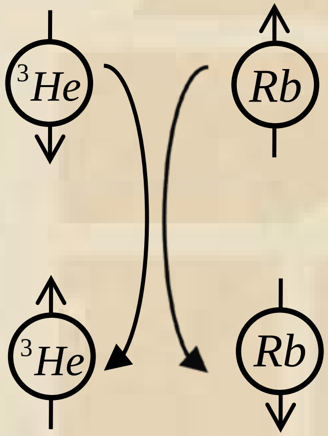
- Two steps in SEOP:

1) Optical Pumping: alkali vapor is spin polarized by the laser.

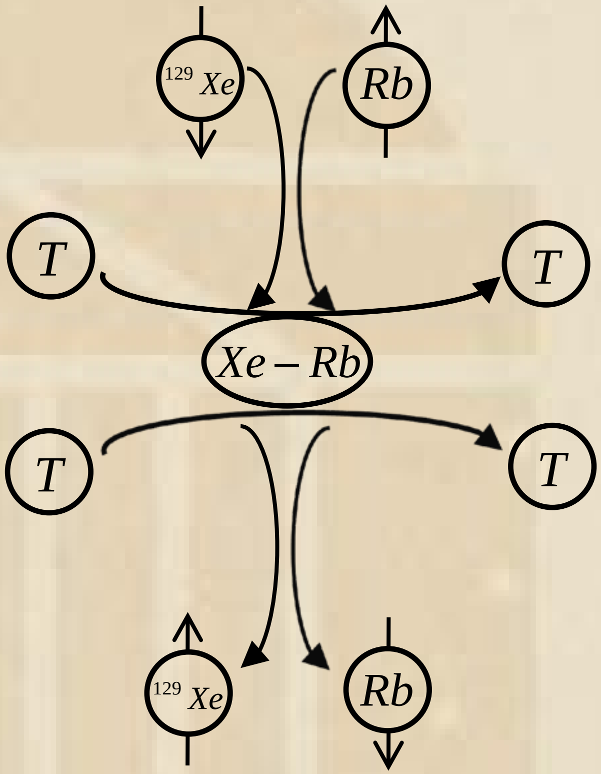


$$P_{\infty}^{Rb} = P_{light}\frac{R}{R+\Gamma_{Rb}} \sim 100\%$$

2) Spin Exchange: spin is transferred to the noble gas nuclei.



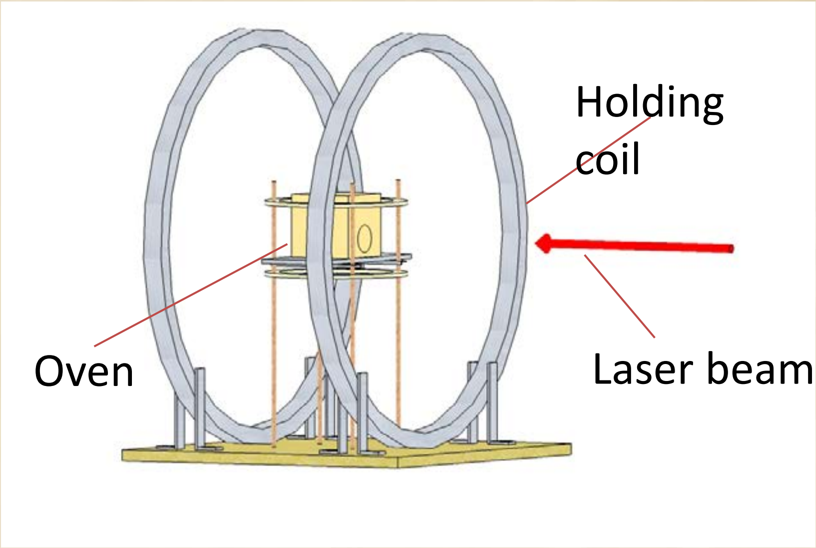
Binary Collision



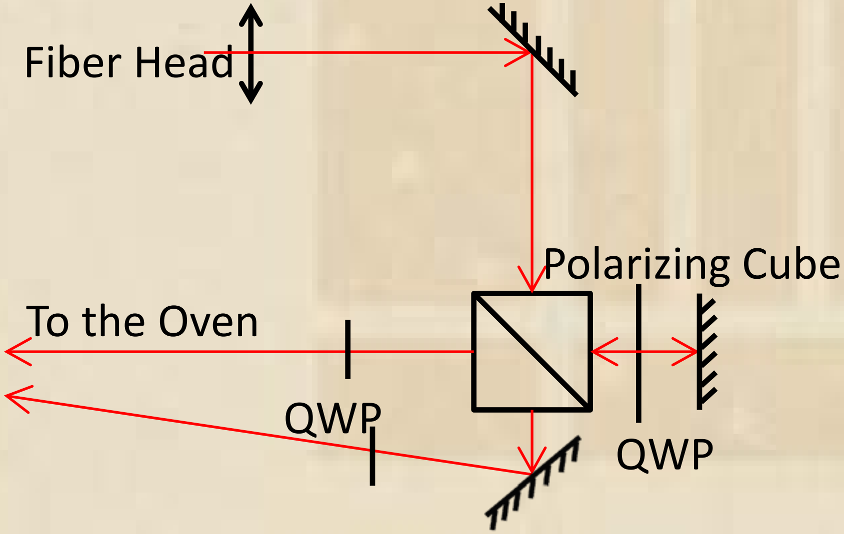
Formation of a Van der Waals molecule

$$P_\infty^g = P_\infty^{Rb} \frac{\gamma_{se}}{\gamma_{se} + \Gamma}$$

SEOP basic setup



A glass cell with some alkali metal, some buffer gas and ^{3}He or ^{129}Xe is placed in the oven. The alkali vapor density is controlled by the oven temperature.

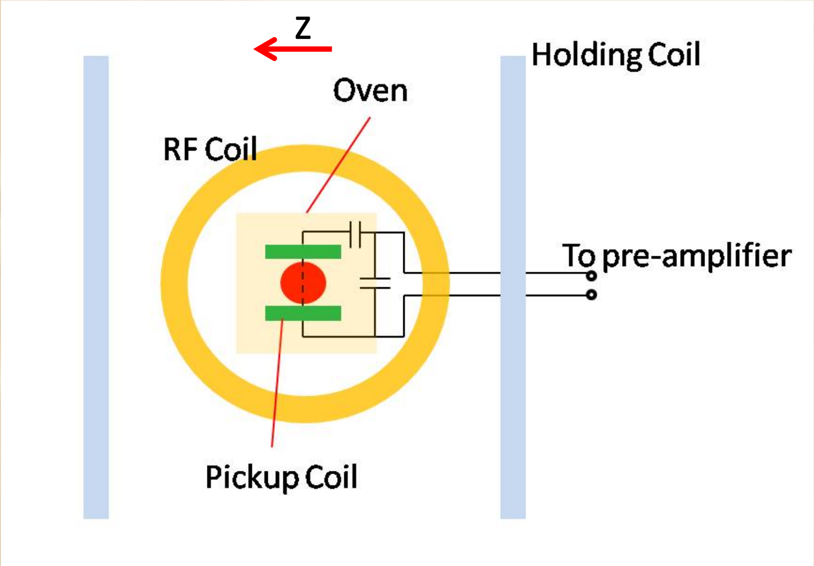


One laser beam is splitted into two beams, both of which are circularly polarized.

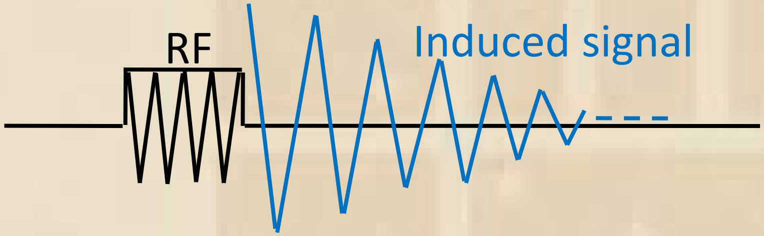
Manipulate the Spins

- Two techniques to study a NMR signal

1. Adiabatic Fast Passage. (AFP)
   a) RF on
   b) Sweep the holding field and take data
   c) RF off
2. Pulsed Nuclear Magnetic Resonance (PNMR).
   a) RF on
   b) RF off
   c) Take data



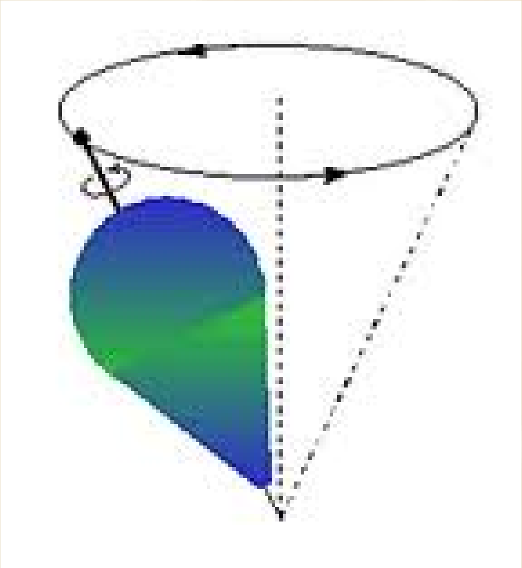
The holding coils, RF coils and pickup coils are perpendicular to each other.



Spins in a Magnetic Field

- Spinning top in gravity field:

$$\frac{d\vec{L}}{dt} = m\vec{R} \times \vec{g}$$



- Spin motion:

$$\frac{d\vec{\mu}}{dt} = \gamma \vec{\mu} \times \vec{B_0}, \quad \vec{\mu} = \gamma \vec{J}$$

- Same solution: **Precession**

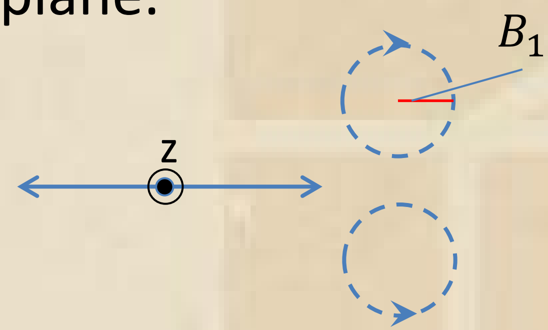
$$\vec{f_0} = -\gamma \vec{B_0}$$

- Effective holding field in a rotating frame:

$$\vec{B_{0eff}} = \vec{B_0} + \frac{\vec{f}}{\gamma}$$

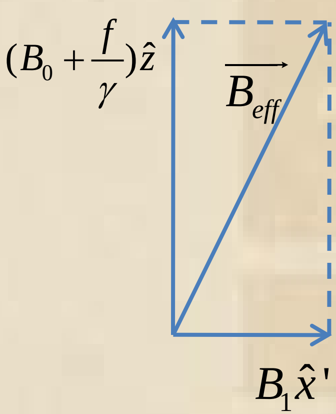
- Interaction with a Radio Frequency (RF) field

Consider applying a RF in the transverse plane.



In a frame rotating at the RF frequency, the effective field is:

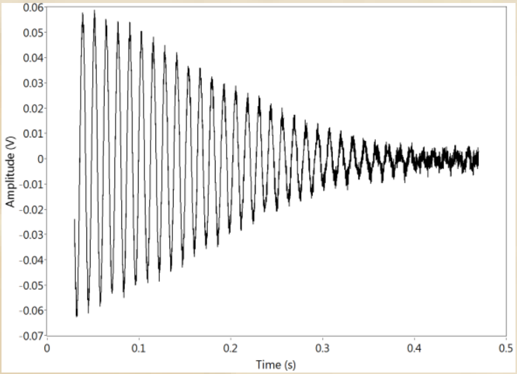
$$\overrightarrow{B_{eff}} = (B_0 + \frac{f}{\gamma})\hat{z} + B_1\hat{x}'$$



If $\overrightarrow{f} = \overrightarrow{f_0} = -\gamma\overrightarrow{B_0}$ ⇒ $\overrightarrow{B_{eff}} = B_1\hat{x}'$ ⇒ *Spin precess along $\hat{x}'$!*

Free Induction Decay (FID)

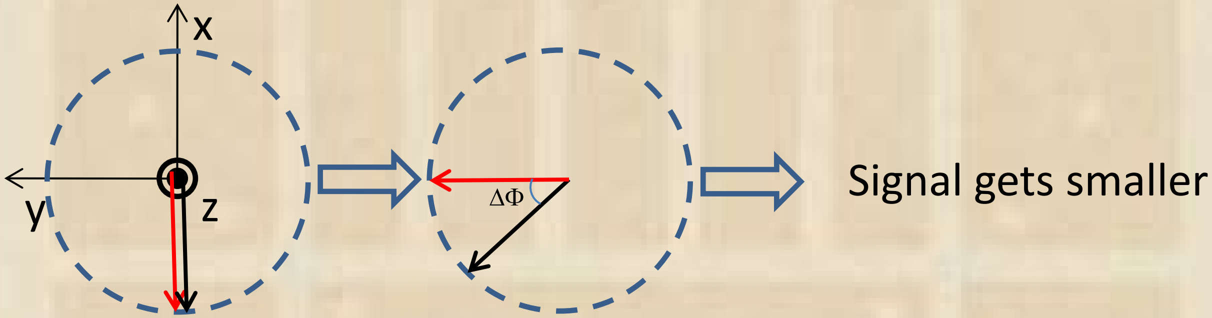
Transvers spins precessing along the holding field with a decaying amplitude will induced an EMF in the pick up coil.



Two reasons for the amplitude decay:

1) Internal "Spin-Spin" relaxation time T_2.
2) External relaxation time T_2'. (Due to field inhomogeneity)

Observed T_2 : $\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{1}{T_2^{'}} \approx \frac{1}{T_2^{'}}$



Spins tipped by the RF

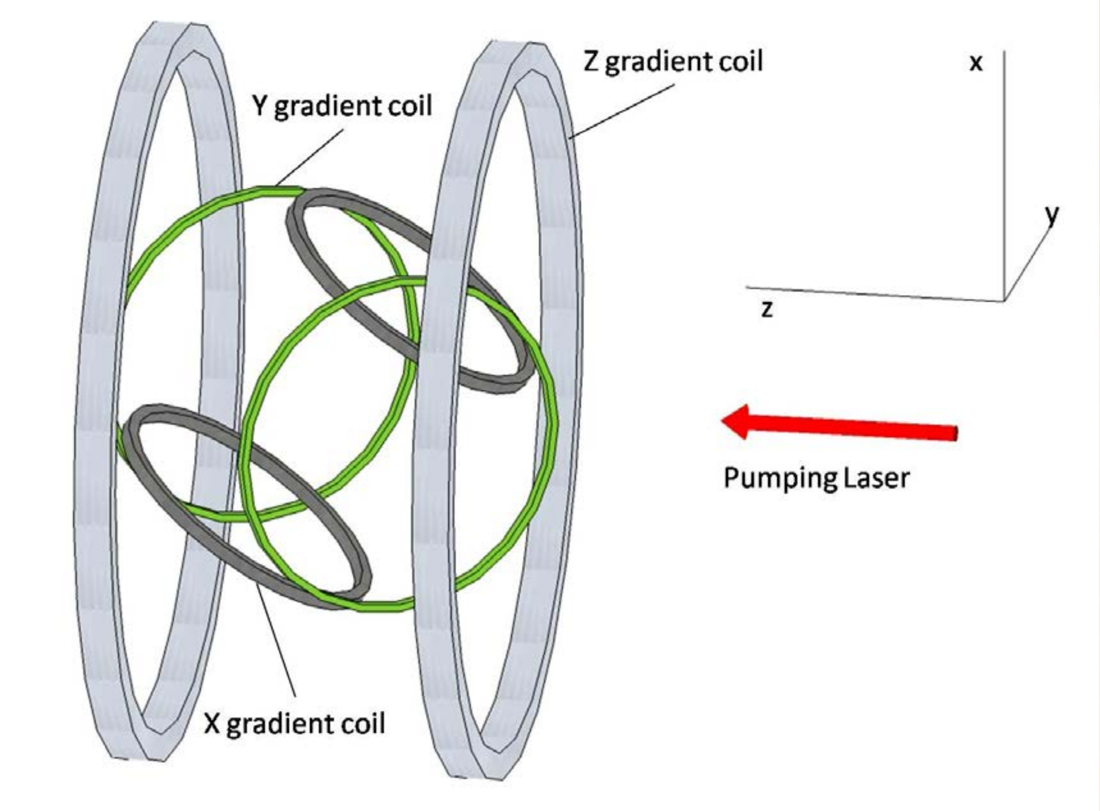
$t = 0, \Delta\Phi = 0$

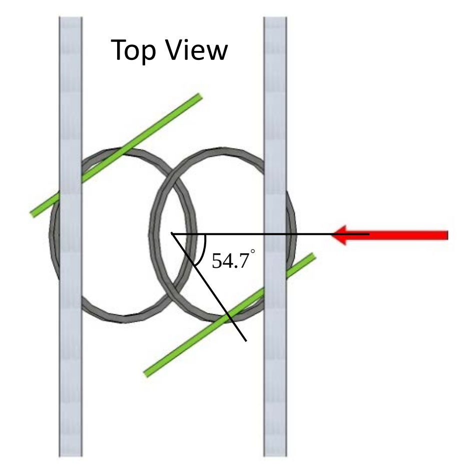
Spins 'fan out'

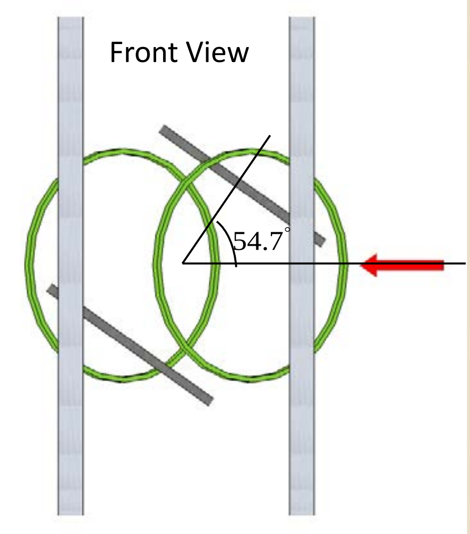
$t = \tau, \Delta\Phi = -\gamma \Delta B \tau$

MRI *setup ≈ SEOP setup + Gradient coils*

MRI Gradient Coils



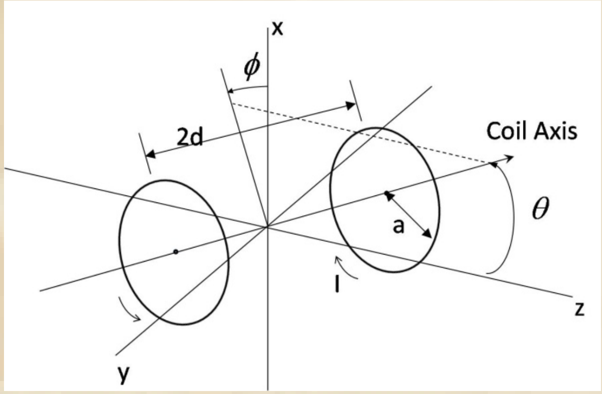




Near anti-Helmholtz coil pairs at special orientations.

Why 54.7° ? (This is usually called the "magic angle" θ_m)

What really matters is how the holding field (Bz) varies.



$$\nabla B = \begin{pmatrix} \partial Bx/\partial x & \partial By/\partial x & \partial Bz/\partial x \\ \partial Bx/\partial y & \partial By/\partial y & \partial Bz/\partial y \\ \partial Bx/\partial z & \partial By/\partial z & \partial Bz/\partial z \end{pmatrix}$$

$$= 3\kappa I \begin{pmatrix} \sin^2(\theta)\cos^2(\phi)\text{ -1/3} & \sin^2(\theta)\sin(\phi)\cos(\phi) & \sin(\theta)\cos(\theta)\cos(\phi) \\ \sin^2(\theta)\sin(\phi)\cos(\phi) & \sin^2(\theta)\sin^2(\phi)\text{ -1/3} & \sin(\theta)\cos(\theta)\sin(\phi) \\ \sin(\theta)\cos(\theta)\cos(\phi) & \sin(\theta)\cos(\theta)\sin(\phi) & \cos^2(\theta)-1/3 \end{pmatrix}$$

$$\kappa = \frac{3\pi n a^2 d}{5(d^2+a^2)^{5/2}}\ G(cm\ A)^{-1}$$

The magic angle is special because it eliminates the z gradient. $\cos^2(\theta_m)-1/3=0$

Z gradient: $\theta = 0, \ \phi = 0.$

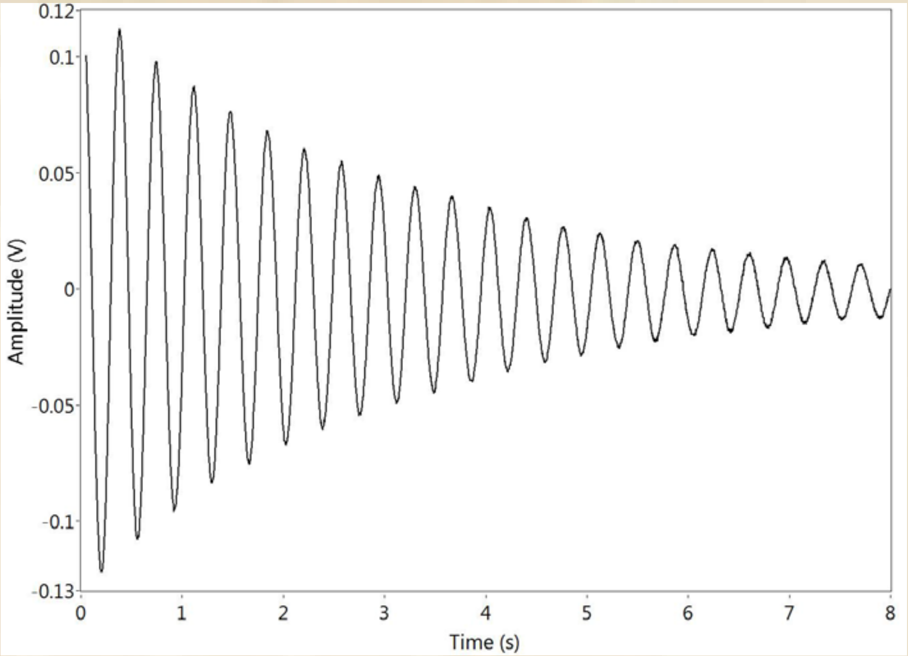
$$\nabla B(0,0) = \begin{pmatrix} \partial Bx/\partial x & \partial By/\partial x & \partial Bz/\partial x \\ \partial Bx/\partial y & \partial By/\partial y & \partial Bz/\partial y \\ \partial Bx/\partial z & \partial By/\partial z & \partial Bz/\partial z \end{pmatrix} = \kappa I \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 2 \end{pmatrix}$$

X gradient: $\theta = \theta_m, \ \phi = 0.$

$$\nabla B(\theta_m, 0) = \kappa I \begin{pmatrix} 1 & 0 & \sqrt{2} \\ 0 & -1 & 0 \\ \sqrt{2} & 0 & 0 \end{pmatrix}$$

Y gradient: $\theta = \theta_m, \ \phi = 90°.$

$$\nabla B(\theta_m, 0) = \kappa I \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & \sqrt{2} \\ 0 & \sqrt{2} & 0 \end{pmatrix}$$



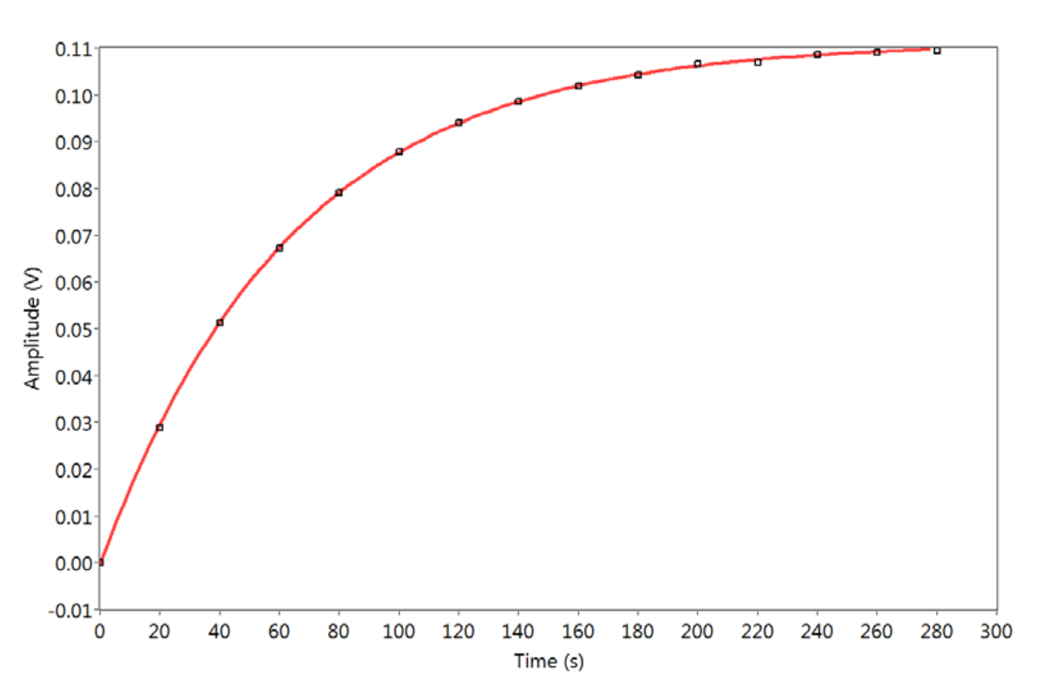
Purposes of the Gradients:

•All the three gradients are used to trim the holding field so that the Free Induction Decay has a longer T_2^*. (less than 200 ms without trimming)

•We take 2D images without slice selection. X and Y gradients are applied as imaging gradients to acquire images of the sample projected on the XY plane.

Xe-129 MRI Procedure

1, Polarize the sample by SEOP. Our sample is a X shaped glass cell with 2.8 atms of isotopically enriched ^{129}Xe. We keep the oven at 85 C and the polarization reaches 5% in 4 mins.



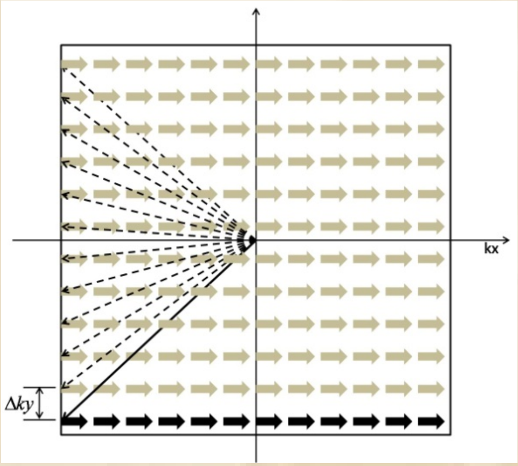
Why 85 C?

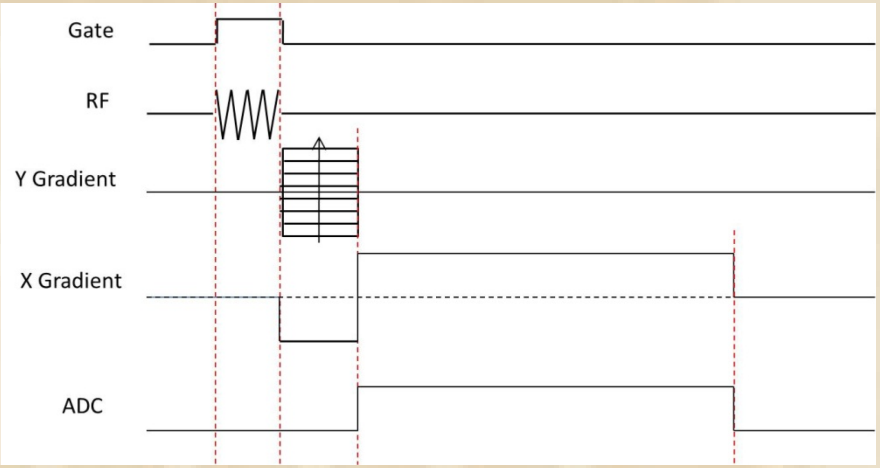
$$P_\infty^{Rb} = P_{light} \frac{R}{R + \Gamma_{Rb}}$$

$$P_\infty^{g} = P_\infty^{Rb} \frac{\gamma_{se}}{\gamma_{se} + \Gamma}$$

2, Excite the spins to the transverse plane. Apply appropriate Gradients and record the data. Only one line of k space data is taken.

$$k = 2\pi\gamma G t,$$



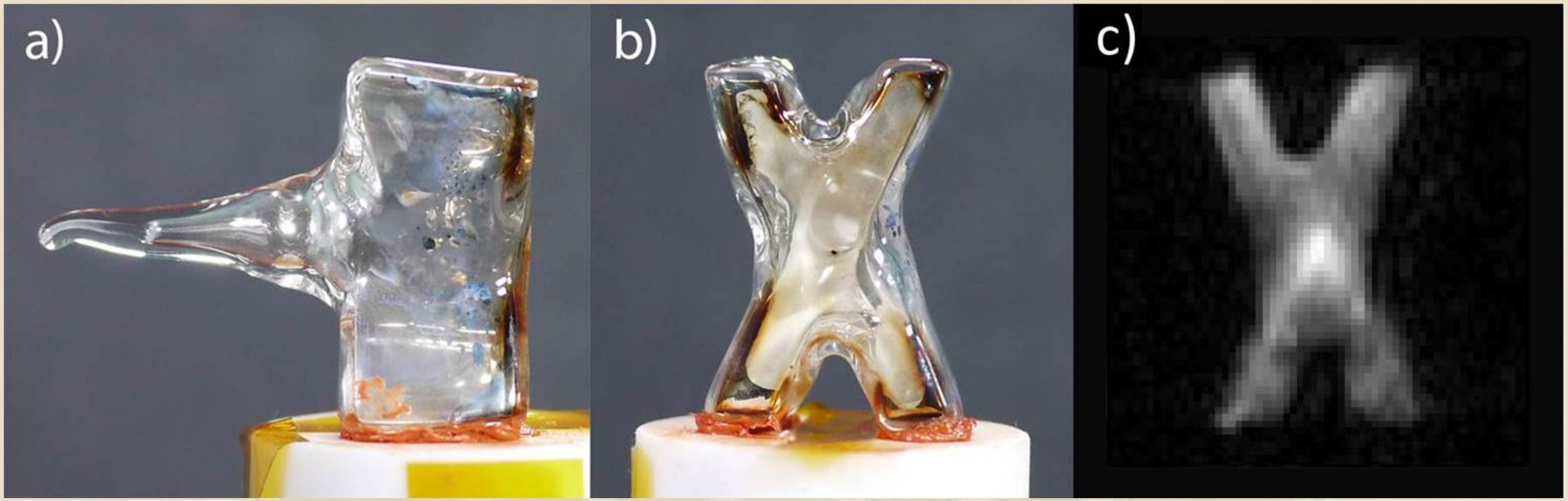


While traveling in k space, the spins precess in a controlled manner and the interference signal is recorded.

3, Repeat step 1 and 2 to collect more data in k space. We take 32 lines in k space and the whole procedure takes 2 hours.

4, Image reconstruction. $s(k) \xleftrightarrow{\text{Fourier Transform}} \rho(x)$

Xe cell and Image



Shown above is an image with 8 averages.

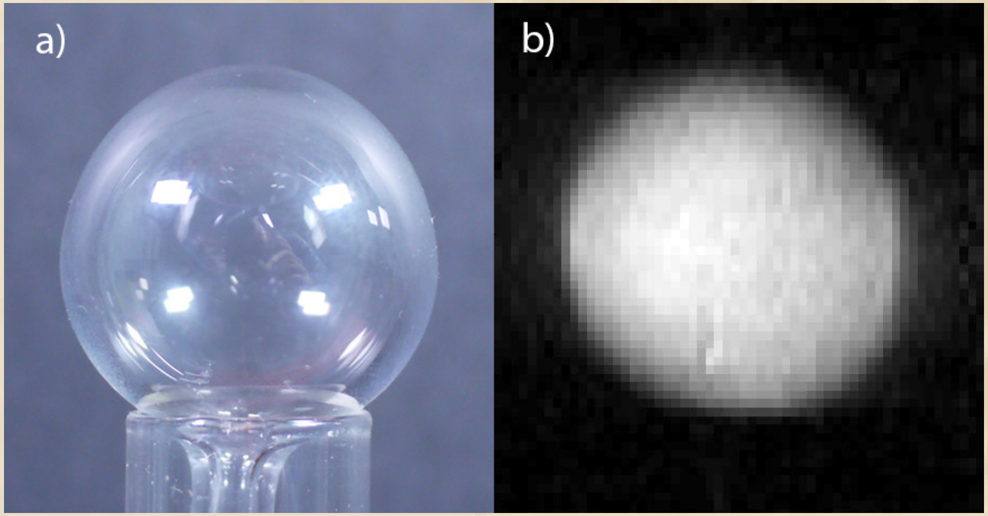
Both x and y direction resolutions are 1mm.
Image artifacts:
1, Central bright area.
2, Dimness in the lower legs.

He-3 MRI Procedure

1. Polarize He-3 gas by SEOP. A much larger magnetization can be achieved.
2. Perform MRI using a Fast Low Angle Shot (FLASH) pulse sequence.
   - Tip the spins by a small angle. Apply necessary gradients and take data for one line.
   - Repeat 32 times.

Advantages of FLASH Imaging:

1. Only polarize once.
2. Much faster.



He cell (2.8 atm) and its image
Resolution: 1mm

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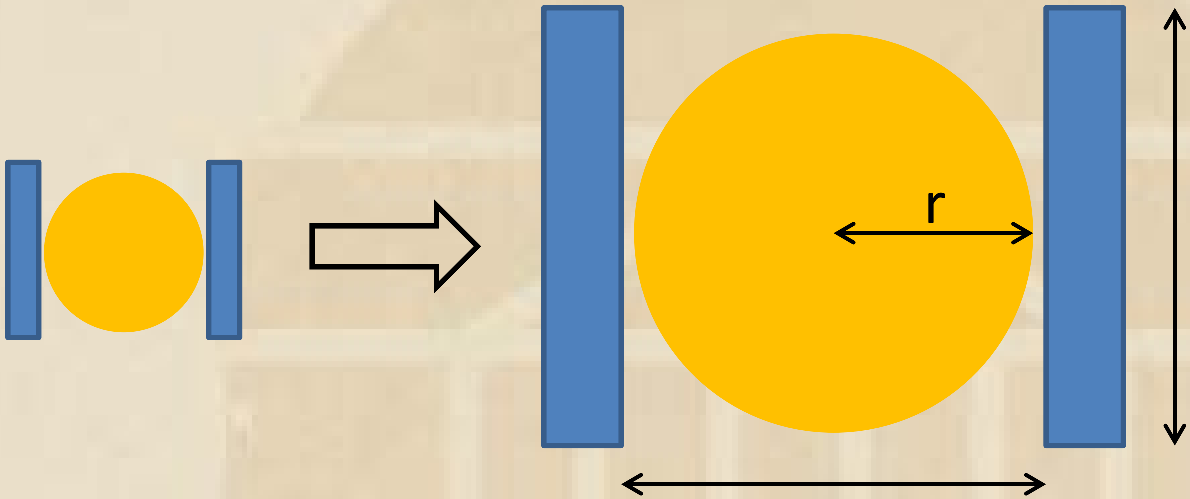
Small animal MRI

Even "small" animals are still bigger than our pickup coils (1").
Bigger pickup coils need to be built for bigger subjects.



$$Signal \propto r^3 \cdot r^2 \cdot r^{-3} = r^2$$

$$Noise \propto r^2$$

S/N is a constant.

However, gas density will be lower… but we can perform MRI in a well shielded room.

2.8 atm ⇨ 1 atm

Pickup noise ⇨ Johnson noise

Thanks!