INTRODUCTION TO MRI

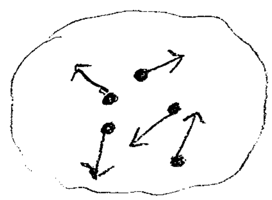
- ATOMS WITH AN ODD NUMBER OF NUCLEONS (^{1}H, ^{31}P, ^{13}C, ^{23}Na) POSSESS A NUCLEAR SPIN ANGULAR MOMENTUM. YOU CAN THINK OF THE NUCLEUS OF SUCH ATOMS AS A SPINNING CHARGED SPHERE THAT GIVES RISE TO A SMALL MAGNETIC MOMENT.

MAGNETIC MOMENT (LIKE A LITTLE BAR MAGNET)

NUCLEUS W/ ODD # OF NUCLEONS

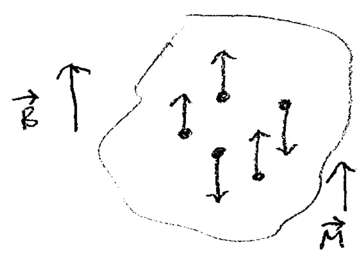
WE CALL THIS A "SPIN"

- IN THE ABSENCE OF A MAGNETIC FIELD THESE SPINS ARE RANDOMLY ORIENTED AND THE NET MAGNETIC MOMENT $\vec{M}$ ACROSS A MACROSCOPIC COLLECTION OF SPINS AVERAGES TO ZERO.



NET MAGNETIC MOMENT $\vec{M} = 0$

HOWEVER, WHEN AN EXTERNAL MAGNETIC FIELD $\vec{B}$ IS APPLIED, THE SPINS ALIGN IN THE DIRECTION OF THE FIELD (PARALLEL OR ANTIPARALLEL). MORE ALIGN PARALLEL, GIVING A NET MAGNETIZATION $\vec{M}$!



NET MAGNETIC MOMENT $\vec{M}$ REMAINS IN DIRECTION OF $\vec{B}$ FOR THE COLLECTION OF SPINS!

- THIS PHENOMENON IS CALLED MAGNETIC POLARIZATION.

  THE DEGREE OF POLARIZATION (MAGNITUDE OF $\vec{M}$ FOR A COLLECTION OF SPINS) INCREASES WITH THE STRENGTH OF APPLIED FIELD $\vec{B}$.

- THIS STATE WHERE SPINS ARE ALIGNED PARALLEL OR ANTIPARALLEL TO THE FIELD OCCURS AT THERMAL EQUILIBRIUM, WHEN $\vec{M}$ IS ALIGNED WITH FIELD $\vec{B}$ AND NOT CHANGING W/ TIME.

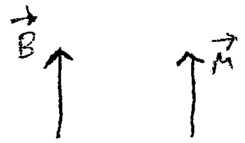
- SO WHAT HAPPENS IF WE COULD KNOCK OUR MAGNETIZATION VECTOR $\vec{M}$ OUT OF ITS EQUILIBRIUM STATE??

<u>ANSWER</u>: THE BEHAVIOR OF THE MAGNETIZATION VECTOR $\vec{M}$ IS GOVERNED BY THE <u>BLOCH EQUATION</u>:

$$\frac{d\vec{M}}{dt} = \underbrace{\vec{M} \times \gamma \vec{B}}_{} \underbrace{- \frac{M_x \hat{\imath} + M_y \hat{\jmath}}{T_2} - \frac{(M_z - M_0)\hat{k}}{T_1}}_{}$$

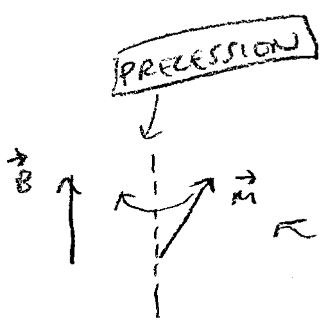
FOCUS ON THIS FOR A MOMENT. IF WE CAN "TIP" $\vec{M}$ AWAY FROM THE DIRECTION OF $\vec{B}$, WHAT HAPPENS??

LET'S IGNORE THESE FOR NOW. THESE TWO TERMS ARE WHAT CAUSES $\vec{M}$ TO "RELAX" BACK TO THERMAL EQUILIBRIUM OVER TIME. WE'LL DISCUSS IN GREAT DETAIL LATER.



← THERMAL EQUILIBRIUM, $\vec{M} \times \gamma \vec{B} = 0$!

SO $\frac{d\vec{M}}{dt} = 0 \Rightarrow$ NO CHANGE! (EQUILIBRIUM... :))



← $\vec{M} \times \gamma \vec{B}$ IS NOW A VECTOR COMING OUT OF THE PAGE! $\frac{d\vec{M}}{dt}$ IS IN THAT DIRECTION.

$\vec{M}$ BEGINS TO <u>PRECESS</u> AROUND THE DIRECTION OF $\vec{B}$ AT A FREQUENCY $\boxed{\omega = \gamma B}$ OR $\boxed{f = \frac{\gamma}{2\pi} B}$ <u>"LARMOR FREQUENCY"</u>

- THIS IS THE "RESONANCE" IN MAGNETIC RESONANCE IMAGING!
- γ IS THE <u>GYROMAGNETIC RATIO</u>, AND IS DIFFERENT FOR DIFFERENT NUCLEI!

SOME KEY TAKE AWAYS:

- AN APPLIED MAGNETIC FIELD $\vec{B}$ INDUCES A NET MAGNETIC POLARIZATION $\vec{M}$ (IN THE DIRECTION OF $\vec{B}$ AT EQUILIBRIUM) ACROSS A MACROSCOPIC COLLECTION OF SPINS.

- IF $\vec{M}$ IS NOT ALIGNED WITH $\vec{B}$, THE FIRST TERM IN THE BLOCH EQUATION REQUIRES PRECESSION OF $\vec{M}$ ABOUT THE DIRECTION OF $\vec{B}$ AT THE LARMOR FREQUENCY γB.

- VERY IMPORTANT: NOTICE THAT THE FREQUENCY OF PRECESSION IS LINEARLY PROPORTIONAL TO THE MAGNITUDE OF $\vec{B}$! IF WE INCREASE OR DECREASE THE MAGNITUDE OF THE APPLIED FIELD, WE VARY THE RESONANCE (OR PRECESSIONAL) FREQUENCY OF $\vec{M}$.

- THE VECTOR $\vec{M}$ WON'T PRECESS FOREVER. THE OTHER TWO TERMS IN THE BLOCH EQUATION SHOW HOW IT GRADUALLY REALIGNS WITH $\vec{B}$ (BUT IT CONTINUES TO PRECESS OR RESONATE AS IT RELAXES BACK TO EQUILIBRIUM!).

- SOMETIMES WE CALL $\vec{M}$ ITSELF A "SPIN" THAT WE ARE TIPPING, BUT REMEMBER THIS IS A MACROSCOPIC EFFECT ACROSS A COLLECTION OF SPINS.

- THIS IS A CLASSICAL TREATMENT. THE QUANTUM PICTURE IS BOTH MORE INTERESTING AND LESS INTUITIVE. FOR THE PURPOSES OF THIS CLASS, THE CLASSICAL DESCRIPTION IS ADEQUATE.

NOW, YOU MIGHT BE ASKING YOURSELF HOW YOU ACTUALLY TIP $\vec{M}$ AWAY FROM $\vec{B}$ TO GET PRECESSION...

EXCITATION:

- TIPPING $\vec{M}$ AWAY FROM THE DIRECTION OF $\vec{B}$ IS CALLED "EXCITATION". WE ARE EXCITING THE RESONANT PRECESSION IN THE SPIN $\vec{M}$.

- EXCITATION IS ACCOMPLISHED BY HITTING THE SPIN $\vec{M}$ WITH AN RF FIELD TUNED TO THE LARMOR FREQUENCY. THIS EFFECTIVELY STARTS $\vec{M}$ PRECESSING AND "DRAGS" IT AWAY FROM THE DIRECTION OF $\vec{B}$.

SOURCE OF THE NMR SIGNAL

- WHEN WE TURN OFF THE RF, THE SPIN CONTINUES TO PRECESS, PRODUCING IT'S OWN RF SIGNAL AT THE LARMOR FREQUENCY!
- WE CAN DETECT THAT RF SIGNAL W/ A COIL $\Rightarrow$ THIS IS THE NMR SIGNAL.

- ANALOGY OF A CHAMPAGNE GLASS RESONATING TO SOUND.

COMPONENTS OF AN MRI MACHINE:

1. $\boxed{B_0}$: BIG SUPERCONDUCTING MAGNET THAT PRODUCES OUR MAIN POLARIZING FIELD

   - VERY STRONG TO GET GOOD POLARIZATION (UP TO ~3 TESLA IN CLINICAL SCANNERS)
   - ALWAYS ON!!
   - VERY HOMOGENEOUS
   - SETS THE FUNDAMENTAL LARMOR FREQUENCY OF THE SYSTEM (TOGETHER WITH γ OF THE NUCLEUS $\Rightarrow$ ^1H)
   - BY CONVENTION, B_0 IS IN THE Z DIRECTION (DOWN THE BORE OF THE MAGNET) $\Rightarrow$ ALSO CALLED THE LONGITUDINAL DIRECTION.

2. RADIOFREQUENCY FIELD B_1: TYPICALLY AN RF COIL INSERTED INSIDE THE BIG SUPERCONDUCTING B_0 MAGNET.
   - RF RESONATOR TUNED TO THE LARMOR FREQUENCY
   - PRODUCES RF FIELD THAT IS CIRCULARLY POLARIZED IN THE XY PLANE (PERPENDICULAR TO Z)
   - USED IN TRANSMIT MODE TO EXCITE OR TIP SPINS.
   - USED IN RECEIVE MODE TO DETECT NMR SIGNAL (ALTHOUGH THIS COULD BE ANOTHER COIL OR ARRAY OF COILS)

3. LINEAR GRADIENT FIELD G_x
4. LINEAR GRADIENT FIELD G_y
5. LINEAR GRADIENT FIELD G_z

- ELECTROMAGNETS BUILT INSIDE THE MAIN POLARIZING MAGNET
- CAN BE TURNED ON OR OFF
- CHANGE THE Z-COMPONENT OF THE MAIN B FIELD LINEARLY IN THE X, Y, OR Z DIRECTION RESPECTIVELY.
- USED TO INDUCE LINEAR VARIATIONS IN THE LARMOR FREQUENCY ACROSS THE BODY IN THE X, Y, OR Z DIRECTION.
- ESSENTIAL FOR SPATIAL LOCALIZATION OF SPINS PRODUCING THE NMR SIGNAL!!